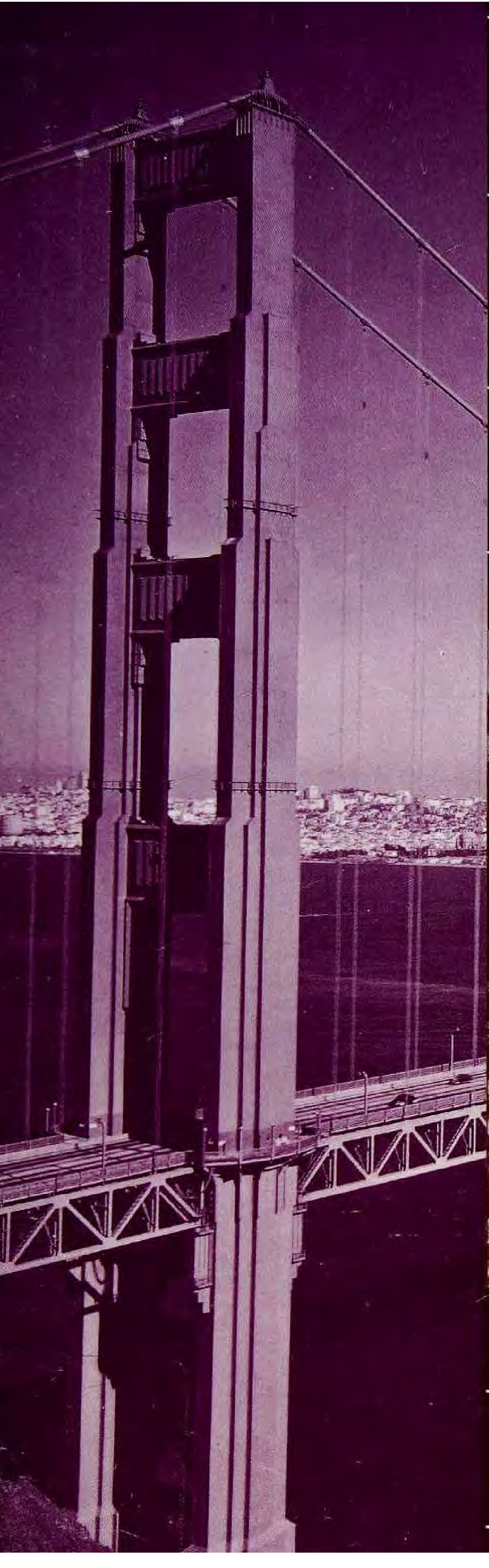
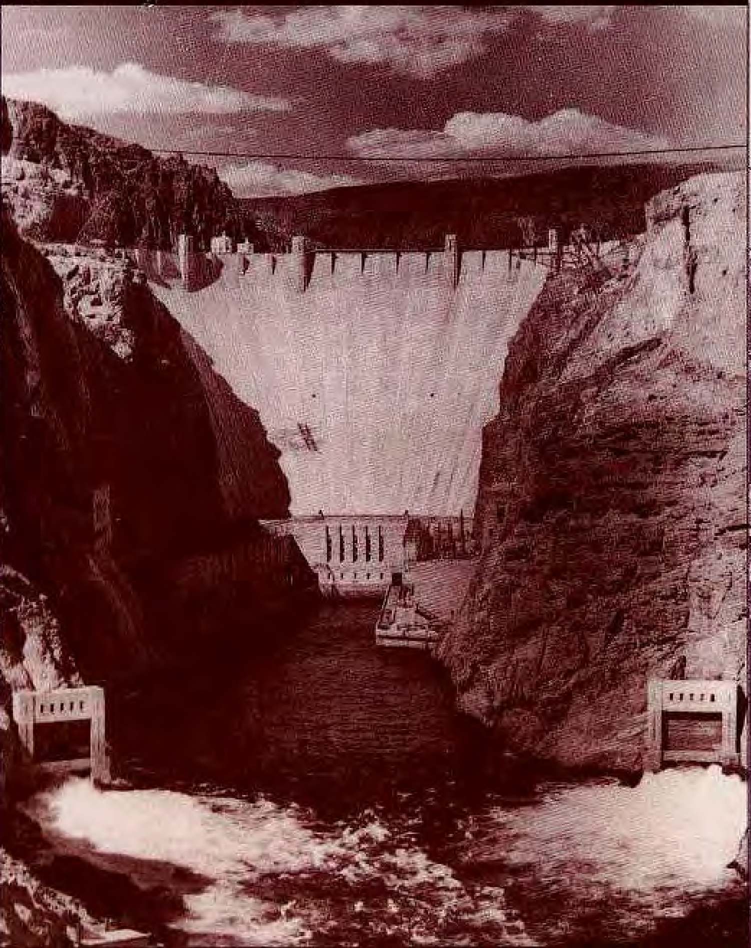


Civil Engineering Materials



Shan Somayaji

CIVIL ENGINEERING MATERIALS

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PRENTICEHALL, Englewood, Cliffs, NewJersey 07632

Library of Congress Cataloging-in-Publication Data

Somayaji, Shan
Civil engineering materials/ Shan Somayaji
p. cm.
Includes bibliographical references and index.
ISBN 0-13-177643-6
I. Materials. I. Title.
TA403.S598 1995
624.1'8--dc20 94-15484
CIP

Acquisitions editor: **WILLIAM ZOBRIST**
Editorial/production supervision
and interior design: **RICHARD DeLORENZO**
Copy editor: **BARBARA ZEIDERS**
Cover design: **DeLUCA DESIGN**
Production coordinator: **DAYID DICKEY**
Editorial assistant: **PHYLLIS MORGAN**
Supplements editor: **ALICE DWORKIN**

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A Paramount Communications Company
Englewood Cliffs, New Jersey 07632

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Printed in the United States of America

10987654

ISBN D-13-177643-b

PRENTICE-HALL INTERNATIONAL (UK) LIMITED, *London*
PRENTICE-HALL OF AUSTRALIA PTY. LIMITED, *Sydney*
PRENTICE-HALL CANADA INC., *Toronto*
PRENTICE-HALL HISPANOAMERICANA, S.A., *Mexico*
PRENTICE-HALL OF INDIA PRIVATE LIMITED, *New Delhi*
PRENTICE-HALL OF JAPAN, INC., *Tokyo*
SIMON & SCHUSTER ASIA PTE. LTD., *Singapore*
EDITORA PRENTICE-HALL DO BRASIL, LTDA., *Rio de Janeiro*

DEDICATION

The text
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Preface

This text is intended for an introductory course on civil engineering materials, usually taken by students of engineering, construction, architecture and technology in the Junior year. It is assumed that the student has completed a basic course on solid mechanics or strength of materials.

A course on properties of engineering materials generally forms a link between the study of solid mechanics and courses on structural design concepts and methods. The ideas of equilibrium and deformation from the course on solid mechanics are needed to describe material behavior and its properties which form the foundation of structural design principles. Design is a process, iterative in nature, of designing a product or a structure that is yet to be built and constructed. The construction of a structure requires a thorough understanding of fabrication, application, field testing, and properties of materials. Thus, a thorough knowledge of properties and performance of materials and construction practices are required to develop, design, and build a safe, economical, and durable structure.

An introductory course on materials of construction or civil engineering is commonly set on the following aspects:

- Physical, mechanical, and other important properties of materials
- Fabrication or method of manufacture
- Durability and long-term, performance
- Specifications and standards
- Application or methods of use
- Laboratory testing procedure
- Material testing procedures history

This text is designed to embrace all these aspects. although the extent of coverage of each may vary from one material to another. Very little, if any, importance is given to chemical properties or characteristics of microstructure of materials, as civil and construction engineering professionals are, in general, not heavily interested in them. Essentially, the focus is on explaining properties and behavior which emphasize concepts from solid mechanics and are required in the understanding of design principles.

Common materials of construction that are dealt with in the text are portland cement concrete, masonry, wood and wood products, iron, steel, plastics, and bituminous materials. Chapter 3 deals with concrete and other cementitious materials (mortar, grout, etc.). A brief introduction to various types of concrete such as fiber-reinforced concrete, reinforced concrete, and precast concrete is also given in this chapter. Various types of masonry units and masonry are discussed in Chapter 4. Methods of construction, properties and specifications are also described. Chapter 5 describes properties of wood, wood products such as glulam and plywood, and lumber, grading of lumber and wood products, and wood construction. Bituminous materials such as tars, pitches and asphalts, grades of asphalt, and asphalt pavements are described in Chapter 6. Iron, reinforcing steel, and structural steel are dealt with in Chapter 7. Properties and uses of plastics and soil are covered in Chapter 8.

Many of these materials are made as composites, by combining various other materials, and a study of the primary material requires an understanding of the basic or raw materials. Thus, a study on aggregates which are required in the construction of portland cement concrete, mortar, grout, masonry, and asphalt concrete are described (Chapter 2) before introducing the *latter.* A brief review of properties of soil as a construction material is done in Chapter 8.

As this is an introductory text on materials, the author felt that the presentation should be as simple as possible and devoid of research ambiguities or summaries. So, the writing style came from a need to generalize material behavior as much as possible so that the student understands the 'general characteristics' in terms of properties and uses. Of course, properties of civil engineering materials depend on a number of variables originating from several sources such as raw materials, method of manufacture, environment, workmanship, method of testing, and age. Due to this, one could question the validity of generalization and the outcome. But all can agree that an introductory course on materials should be able to present a general picture of overall material behavior, and it is this understanding which prompted the style of presentation.

Some of the information on properties, specifications, and uses of few materials are repeated at several places within the text. The purpose of this design is two-fold:

First, is the pedagogical notion that the student understands better through repetition, and the second is that there exists many variations in the subject matter as well as style as taught in various schools in the country, and this demands that each chapter/section be complete with all relevant information without the need to go back and forth within the text.

To illustrate the second point, details about reinforcing steel can be found in Chapter 3: Concrete and other Cementitious Materials and in Chapter 7: Iron and Steel. When the concepts of reinforced concrete are presented, which is explained in the text.

as a composite material made from concrete and reinforcing steel, data on properties and grades of reinforcing steel are required, which are described in Chapter 3. These details are repeated in Chapter 7, wherein physical properties, mechanical properties, types and grades of reinforcing steel and structural steel are described. The author did not find it proper to let the student tum back to Chapter 3 in order to understand the details about steel.

Laboratory testing procedure for selected tests is described at the end of most chapters instead of as an adjunct to the text. This is done to drive a point that laboratory testing is an essential *part* of the study of materials of civil engineering or construction. All the test procedures are based on relevant ASTM specification, but are presented in a manner that makes it more useful and convenient in a classroom atmosphere.

Although a great deal of care is taken to see that the details are current, noncontroversial, and free of error, it is natural to expect errors and omissions due to the vastness in scope and breadth of this material. The author would be very grateful if these are brought to his notice at the following address:

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The author also wishes to acknowledge the valuable contributions of Wei-Chou V. Ping of Florida A&M University/Florida State University and Mumtaz A. Usmen of Wayne State University whose insightful comments in reviewing this manuscript are greatly appreciated.

Shan Somayaji

CHAPTER 1

Introduction

Civil engineering embodies professionals who design, construct, maintain, inspect, and manage public works projects. Such projects include characteristically diverse groups of facilities such as railroads, high-rise office buildings, and sewage treatment centers. The construction may be underground or above ground, offshore or inland, over mile-deep valleys or flat terrains, and through Rocky Mountains or clayey soils. Just the thought that all these creative efforts are made possible through the marvelous innovative spirits of civil engineers is comforting and appealing as well as challenging for prospective civil engineers. These gigantic achievements stand to promote the scope of civil engineering potential.

Although the profession of civil engineering *is* of fairly recent origin [the American Society of Civil Engineers (ASCE), the oldest national engineering society in the United States, was founded in 1852), civil engineering work is as old as humankind. The most ambitious and historically significant projects throughout the history of civilization were built to satisfy human needs for transportation, water, shelter, and disaster control. Although the existence of these needs can be traced back to the origin of civilization, a systematic approach to establishing procedures that meet all our needs by training young minds professionally in all facets of civil engineering is quite new.

In addition to fighting wars and conquering other kingdoms, historical rulers were involved in constructing facilities and building programs that catered to the public spirit. The first Babylonian dynasty of King Hammurabi (about 1800 B.C.) initiated sweeping.

reforms and construction programs documented in historical manuscripts. King Sennacherib (Assyria, 700 B.c.), who was called a great engineer-king, built a dam across the river Tebitu, and from the reservoir thus created, constructed many canals. The canal walls were built from cubes of stone and the floor had a layer of concrete or mortar under the top course of stone to prevent leakage. Nearly all Mesopotamian cities around that time were paved with slabs of stone and brick. The first emperor of the Chin dynasty in China (259-210 B.C.) started the building of the Great Wall of China for protection from the Huns. The Great Roman emperor Constantine I, after his conversion to Christianity, built the city of Constantinople and dedicated it as his capital (A.D. 330).

History shows us that these ancient engineers were innovative and efficient in terms of the type and the method of construction which they employed. Sumerians (around 3000 B.c.) built houses with mud bricks joined by locally available bitumen. They had constructed 18-ft- (5.4m) thick walls on a circumference of about 6 miles (9.6km) to provide refuge to people and cattle. Mesopotamians built mud-brick huts without windows which kept out the sizzling heat of the summer sun. People in southern India and Sri Lanka had houses made of wooden frames and removable reed mat for walls. This type of house, being cheap and practical, is still being built.

Historical sites and ruins show us the skills of ancient builders. At Harappa and Mohenjo-Daro, along the rich alluvial banks of the Indus River (India/Pakistan), there are remains of two large and expertly constructed cities (3000-1500 B.C.). The cities were planned around a central citadel and constructed of good quality burned brick. Elaborate municipal drainage system and complex irrigation system were without parallel during ancient times. During the Eastern Chou dynasty in China (770-250 B.c.), a number of cities were built, usually rectangular or square on a north-south axis, and they had double walls with a moat.

The Assyrians (Mesopotamia, 1100-750 B.c.) knew how to construct buildings that could not be destroyed by fire. Their buildings were made of stone, so that fire burned off the roof only. One of the most important technological discoveries was the introduction of hydraulic cement by Romans around 145 B.C. They discovered that when added to lime mortar, sandy volcanic ash made a material that was strong as rock when dried. They called it *pulvis puteolanus*. Using this material, Romans built aqueducts, bridges, and roads, some of which are still in use. Their standard road was 15 ft (4.5m) wide and had a 4-ft- (1.2m) deep foundation formed of layers of stone, rubble, and concrete topped with a surface of concrete, stone, and powdered gravel. Underground sewage facilities were installed because of the location of their cities in valleys between sharp hills. The walls of their buildings had thin facings of brick, stone, and marble. They built apartment houses of five or more stories and had public latrines that were flushed with water from baths and industrial establishment. Romans also built bridges using semicircular arches using stones.

In Pataliputra (India, 300 B.c.) houses were constructed of wood, and to protect them from fire an elaborate system of fire precautions was enforced. Records show that people built suspension bridges held by iron chains. Ingots of steel made in India were taken to Damascus, where they were converted into sword blades.

The historical records show that the basic materials of construction used in various parts of the world were from the earth or from plants. Every continent in the world possesses.

three basic types of surface characteristics: hard crystalline rocks (such as granite), mountainous belts of folded sedimentary rocks, and plainland basin filled up with sediments. This means that the core of material technology is the same in every part of the world. But different materials have been used in different places, depending on local availability and need.

For example, in Mesopotamia, the most abundant natural resource of the land is mud. Hence the city walls were made of clayey mud. Molding the clay into bricks made it possible to build straight walls without visible weak spots. Brick mold was believed to be a Sumerian invention (around 3000 B.C.), and the use of molds made it possible to manufacture bricks that were flat on all six sides. The bricks were dried from a few days up to 5 years (depending on how strong a brick is required). But independent of the extent of the drying period, the bricks softened and crumbled when they became wet.

This led to the discovery of a new kind of brick-burned brick. The chemical changes in the clay during burning resulted in strong and durable bricks. But these bricks were costly due to the scarcity of fuel and thus were used only on the outside of important buildings. Egyptian temple buildings had stone-paved floors supporting colossal stone columns (hollow), which took up the load from massive stone lintels. The stone was used in temple buildings and for tombs because the Egyptians considered a tomb as a house of eternity and the temple as a house of a million years. Houses, on the other hand, were built of mud and wood, and thus were not durable. Assyrians had used swamp reeds as structural material in house building. A bundle of reeds tied together served as a pillar to hold up a house of light construction. The vast cedar forests of Lebanon supplied timber to Egypt and Mesopotamia, which had little good building timber of their own.

In Babylon (King Nabopolassar, around 600 B.C.), city walls were built using. two walls, one outer and one inner, and filling the space between them with rubble, generally up to ground level. The Ishtar Gate of Babylon (King Nebuchadrezzar, around 550 B.C.) was finished with enameled bricks, blue on the towers and green and pink on the connecting walls. The Babylonian roads were paved with massive stone blocks set in asphalt.

The post-and-beam framing in timber owes its development to the Greeks. They brought into the Mediterranean basin a tradition of using wood, featuring a sloping and pitched roof.

This brief historical perspective of civil engineering construction shows that the materials of construction were, for the most part, of native origin and satisfied environmental compatibility. This statement applies to most basic materials used in today's civil engineering structures, but not for all. Advances in engineering techniques, resource constrains, and cost-cutting measures are responsible for the introduction of quite a number of materials to the construction market. In this book no attempt is made to explain the need to choose a material in any application following detailed reviews of long-term effects and environmental compatibility in addition to immediate financial gains. A material such as asbestos may appeal to many of us due to one or more of its properties (fire resistance in the case of asbestos) as well for financial reasons, but the long-term potential to cause environmental hazards and human discomfort may outweigh the immediate dividends. This aspect of material selection, although beyond the scope of this basic textbook on materials, is central in importance.

1.1 CIVIL ENGINEERING MATERIALS

The basic materials used in civil engineering applications or in construction are:

- Wood
- Concrete
- Bitumen's
- Structural clay and concrete units
- Reinforcing and structural steel

These materials are sometimes called *structural materials.* Added to these materials are plastics, soils, and aluminum. All these materials are used in a number of civil engineering structures, such as dams, bridges, roads, foundations, liquid-retaining structures, waterfront structures, buildings, and retaining walls. The most important highway materials are soils, aggregates, bituminous binder, lime, and cement.

Wood is derived from trees and can be used directly as pieces of lumber obtained from the log or as a raw material in the manufacture of various wood products. Plywood, glulaminated timber, and oriented strand board are some of the wood products used most commonly in construction.

Concrete is a basic construction material made with portland cement as a primary ingredient. Po1tland cement (and other types of cement) are also used in the manufacture of many other construction materials. Concrete is used in combination with other distinctly different materials, such as steel reinforcing bar, polypropylene fibers, and high-strength wires to produce different types of concrete.

Bitumen, which comes in variety of forms, is combined with other raw materials in the construction of pavements, roof shingles, waterproofing compounds, and many others. Structural clay and concrete units, commonly called bricks and blocks, are the principal elements in the construction of masonry walls. Structural steel is used in many forms and shapes for the construction of railroad ties, high-rise buildings, roof trusses, and many more. These basic materials are selected for their properties, performance, availability, aesthetics, and cost. Knowledge of all these aspects is essential in selecting a suitable material for a particular situation.

In addition to the basic materials described above, there are a significant number of secondary materials of construction. Sealants, adhesives, floor and wall coverings, fasteners, and doors and windows come under this category. Most of these materials, also called *nonstructural materials,* are selected based on quality guidelines and aesthetic considerations.

1.2 PROPERTIES OF ENGINEERING MATERIALS

Materials for engineering applications are selected so that they perform satisfactorily during service. The material for use in a highway bridge should have adequate strength, rough surface, and sufficient rigidity. A water-retaining structure can be built using.

materials that are impermeable, crack-free, strong, and do not react with water. A road surface can be built using materials that show little movement under load, are water resistant, and are easy to repair. The performance requirements are not the same for all structures. To evaluate the performance characteristics of engineering materials and to assist in the process of selection of the best material for a particular application, we need to study the properties of materials. In general, most properties of engineering materials are grouped under three major headings:

- Physical prope1ties
- Mechanical properties
- Chemical properties

Physical properties are those derived from properties of matter or physical structure. They include density, porosity or voids, moisture content, specific gravity, permeability, and structure (micro or macro). In addition, properties such as texture, color, and shape come under this classification. The physical properties are helpful in evaluating a material in terms of appearance, weight, permeability, and water retention.

Mechanical properties measure the resistance of a material to applied loads or forces. Some of them reflect the strength of the material, whereas others measure the deformation capacity or stiffness. Strength is a measure of the maximum load per unit area, and can be in tension, compression, shear, flexure, torsion, or impact. When we compare the physical strength of one person with the emotional strength of a second person we know that the two "strengths" are not the same and the comparison is not appropriate. The same reasoning can be applied to desc1ibing the strength of a material: it is important to know the type of strength being dealt with.

But it should be noted that a material can be subjected to a combination of loads which will result in more than one type of stress acting on it. For example, a floor joist may be subjected to loads that cause bending moment and shear as well as torsion. In these situations, measurement of the inherent strength becomes analytically and experimentally complex, and in many situations cannot be done. As in the maintenance of good health in a human body, for which both emotional and physical strength is critical, so is the performance of a construction material, which requires adequate strength of all types.

The deformation capacity or stiffness is measured in terms of elastic modulus, which will be explained later. It is important to note that a knowledge of both the strength (or various types of strength) and deformation capacity of materials is absolutely essential in the selection of a construction material. A high-strength material need not possess a high deformation capacity or stiffness, and vice versa.

In addition to strength and deformation capacity, mechanical properties include other properties, such as brittleness, plasticity, and ductility. Note that all these three properties reflect deformation characteristics of the material.

Chemical properties are those pertaining to the composition and potential reaction of a material. The compounds of composition, such as oxides and carbonates, describe the chemical nature of the material. They explain the way a material behaves in a certain environment. For example, by knowing the principal compounds of cement we are able to choose the type of cement for a particular application. A knowledge of chemical composition of clays is indispensable in evaluating the characteristics that can be expected in burned-brick. Other chemical properties that are noteworthy are acidity, alkalinity, and resistance to corrosion.

In addition to physical, mechanical, and chemical properties, thermal, electrical, magnetic, acoustical, and optical properties are also important in civil engineering. For example, the coefficient of thermal expansion of concrete, which is a thermal property, is fundamental to calculate the expansion potential of a concrete slab. *Thermal properties,* customarily, represent the behavior of a material under heat or temperature. *Acoustical properties* such as sound transmission and sound reflection are important in selecting materials that should provide sound resistance and act as sound barriers. *Optical properties* such as color, light transmission, and light reflection are essential in determining the energy consumption capacity of a material. Properties such as *electrical conductivity* and *magnetic permeability* are needed in materials used in electrical works.

In civil engineering construction, some materials are selected based primarily on their physical properties or physical characteristics, whereas most others are chosen because of their mechanical properties. For example, lightweight aggregates such as pumice and shale are used in the manufacture of lightweight concrete floor slabs, due primarily to their low density. In an area of high seismic activity, structural steel is chosen for columns in a multistory building for its high tensile strength and ductility.

Thus a proper understanding of the environment and constraints in which a particular construction is to be developed is important in the material selection process. The goal of engineering design should be to select the best material for a particular job. An understanding of all relevant properties of various materials available and an appreciation of their performance characteristics are of fundamental importance in achieving this goal. A brief description of general strength and deformation properties are presented in the following sections.

1.2.1 Loads and Stresses

When a solid body is subjected to external forces, called *loads,* the body is deformed, and internal forces are produced (Fig. 1.1). The internal forces which act between consecutive particles, called stresses, are proportional to the external loads. This balancing act between internal and external forces is stated to maintain equilibrium conditions in the body.

To illustrate this theory, let us take the example of a rubber band. When the two ends of the rubber band are pulled apart, the band stretches, which is a deformation or change in length (extension in this example) of the body. The extension gets bigger with increase in the pull, which is the applied force. But each time we increase the force or the pull, the rubber band elongates a little more and then it stops. As long as we hold the force constant, the extension remains unchanged at that point in time. This balancing act between the pull and the stretch explains the equilibrium phenomenon.

External forces

Equilibrium condition

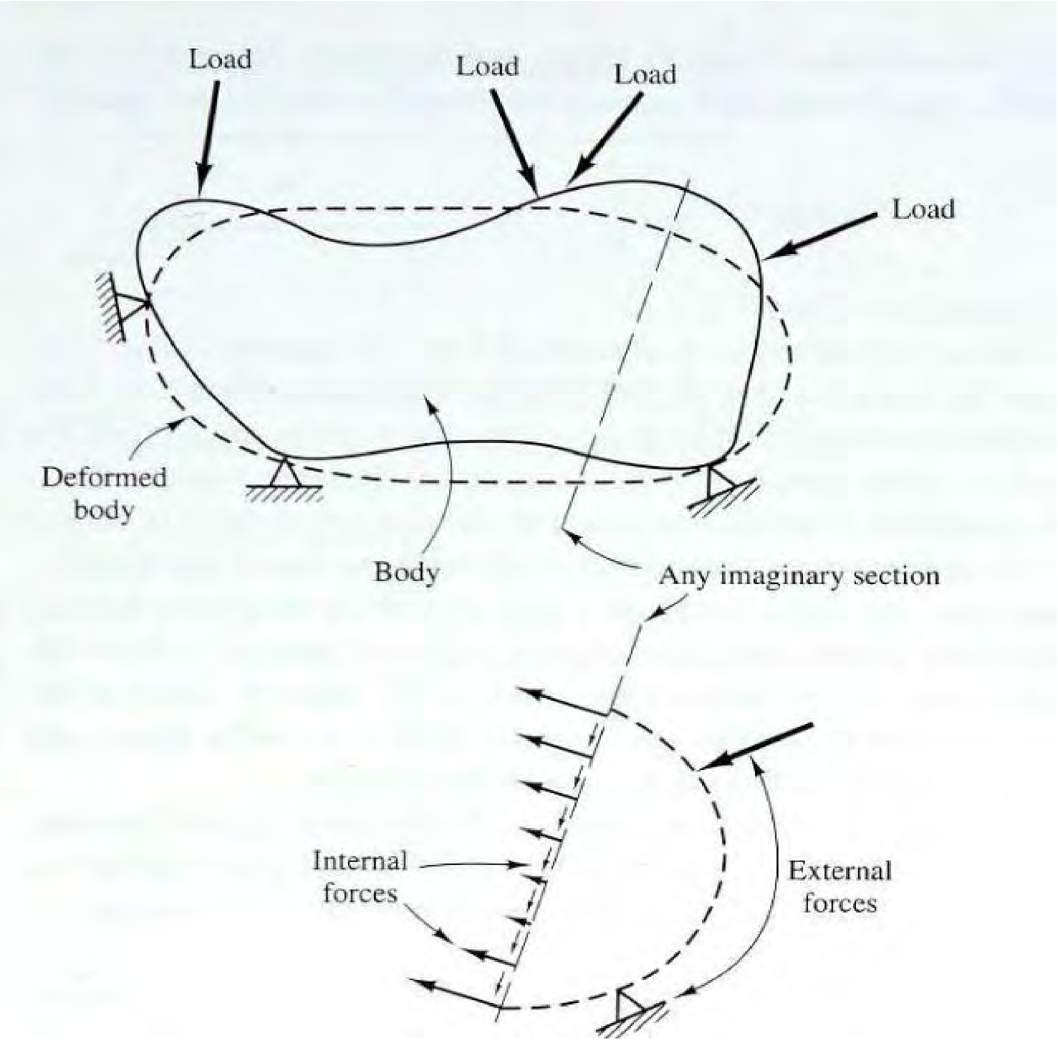


Figure 1.1 Solid body subjected to external forces.

Finally, when the force applied is sufficiently large, the rubber band breaks, which shows the threshold of this theory. If we can now join the broken ends of the band together, the "new" rubber band can once again be used for a rerun of the same experiment. We can repeat the same test all over, ending in the failure of the band a second time. Just before the failure, the external force applied is the maximum as well as the extension, which is proportional to internal forces in the material that makes the band.

Thus it can be stated that the stresses acting on any imaginary section through a body of the material (rubber band in this example) must be in equilibrium with the external forces acting on either side of this section. This theory allows us to calculate stresses and deformation in a material subjected to external forces. But note that this principle of equilibrium applies to a body at rest. When a body is in motion, additional forces from the acceleration should be considered.

In the example of the rubber band, what we notice in the material is its extension. when subjected to pull. Materials undergo extension or contraction, depending on the type of load and the direction of measurement. This change in length immediately following the application of a unidirectional force is called *deformation.* (or *linear deformation).* The deformation per unit length is called *strain.*

Strain is thus a ratio between the change in length and the length along which the change is measured, called *gage length.* It is usually expressed as inches per inch of length (Fig. 1.2).

$$\text{Strain, } e' = e/l$$

where e is the change in length over a length l.

When a 2-in.-long rubber band stretches to a length of 3 in., the deformation is 1 in., the gage length is 2 in., and the strain is 1 in./2 in., or 0.5 in.fin. This means that a 4-in.-long rubber band has to be stretched to a length of 6 in. to have the same Strain as the 2-in. rubber band. In other words, the 4-in. rubber band with 2 in. extension has the same strain as the 2-in. rubber band with 1 in. extension. It can thus be seen that the concept of strain is helpful in comparing the effects of a certain load or force on bodies of different shapes and sizes.

The term *stress* measures the force acting on a unit area of an imaginary section through the body. As indicated earlier, there are as many types of stresses as there are forces. A force acting along the Axis of the member causes *axial stress* or *direct stress* (Fig. 1.3a). When the axial force is in tension, the resulting stress is a *tensile stress,* and when it is in compression, the corresponding stress is *compressive stress.*

Shearing stress is produced by forces that tend to slide one particle upon another, and it acts along or parallel to the cross-sectional plane (stress on a square element in Fig. 1.3b). Note that tensile or compressive stress acts perpendicular to a plane and is thus perpendicular to the shear stress.

A *bending stress* (or *normal stress* or *flexural stress)* is produced by external forces that create bending moment. Due to the action of bending moment, one side of the cross section has tensile stresses (top of the beam in Fig. 1.4) and the other side has compressive stresses (bottom of the beam in Fig. 1.4).

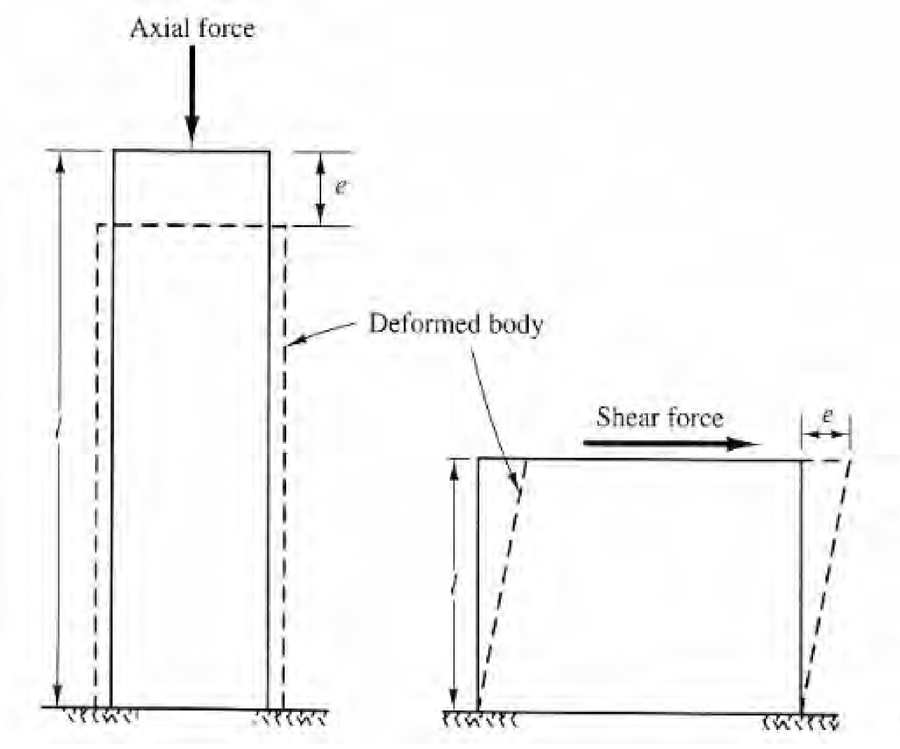
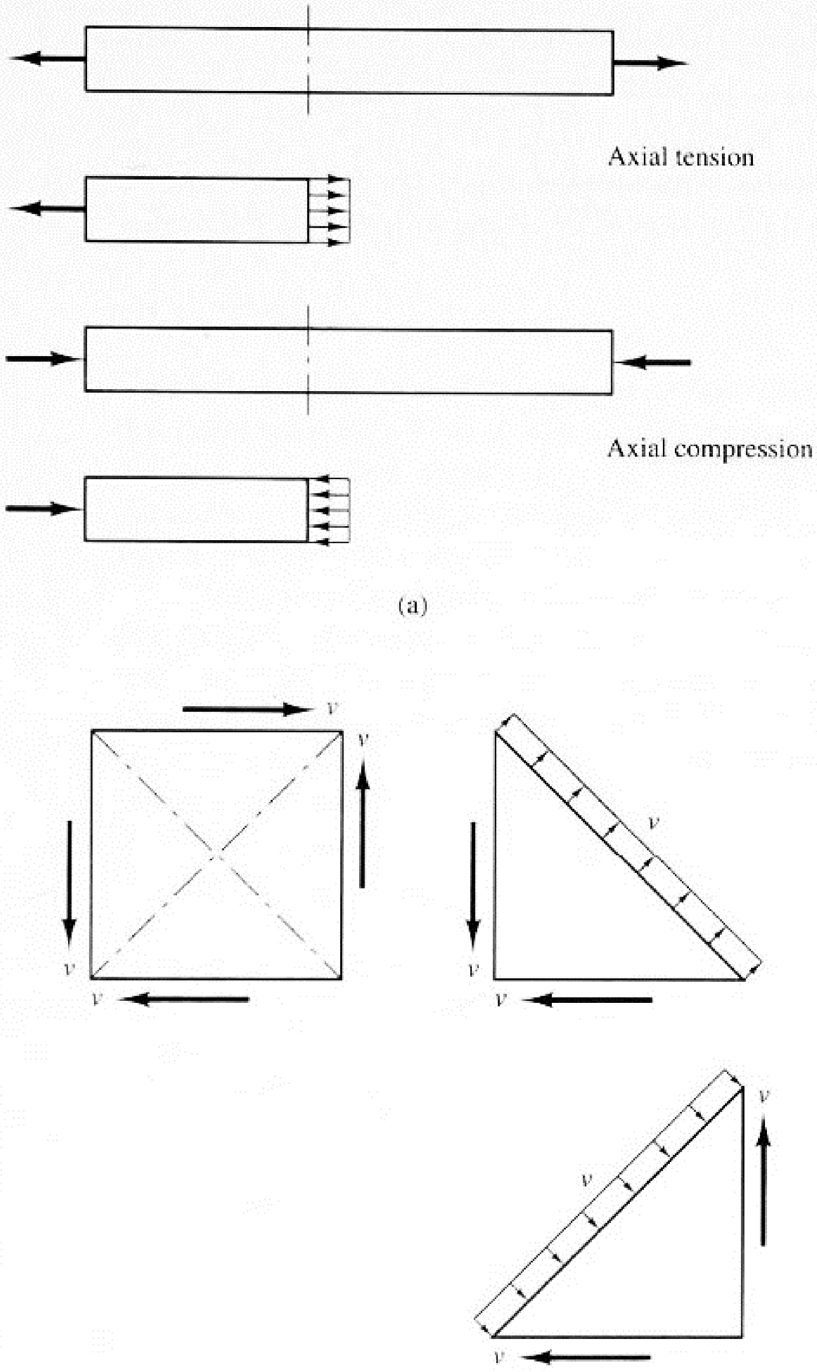


Figure 1.2 Deformation.



(a)

(b)

Figure 1.3 (a) Axial and (b) shear stresses.

1.2.2 Strain

It was pointed out earlier that the change in linear dimension is called deformation. But the term *deformation* is also used to indicate the change in form of a body and may be the result of more than one cause. Thermal changes, moisture loss, and applied loads all cause deformation in the body. When explaining the effects of direct stress, deformation *is* taken to mean the change in linear dimension. But when explaining the effects of shear force, deformation (called *shear deformation)* is the change in length measured parallel

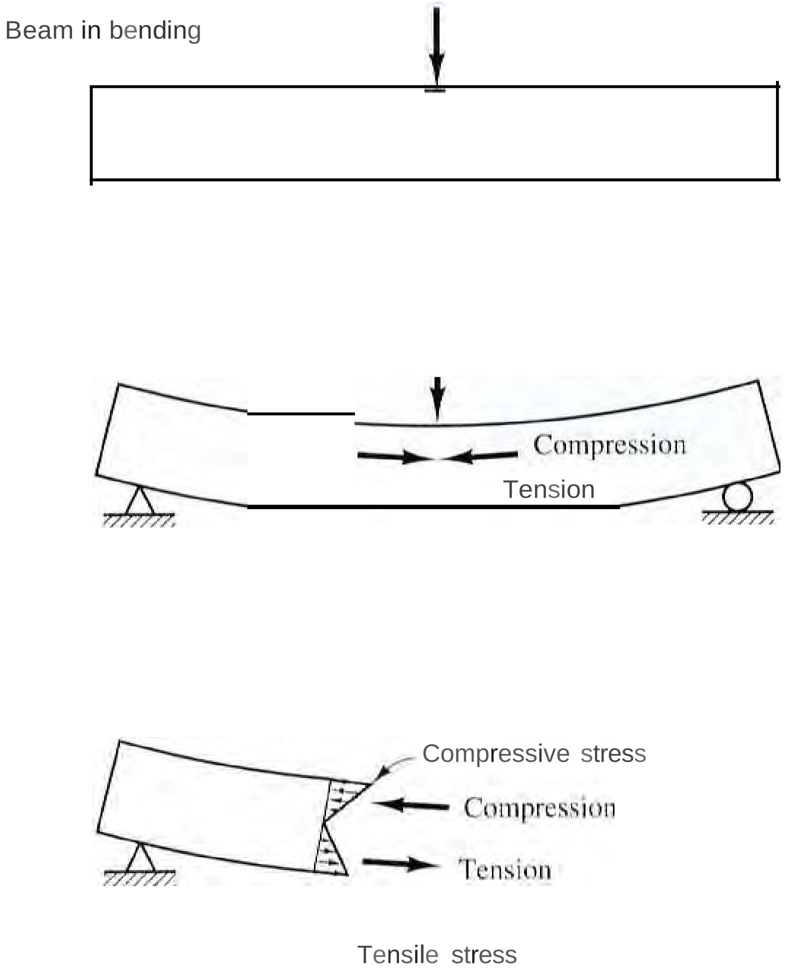


Figure 1.4 Bending stresses.

to the direction of the shear forces. But shear strain is computed as the shear deformation per unit length perpendicular to the direction of the shear force (Fig. 1.2). Thus the shear strain is the change in angle between the two sides and is expressed in radians.

When a body is subjected to an axial stress (tensile or compressive), deformation takes place not only in the axial direction but also in directions perpendicular to this. The ratio of lateral (perpendicular to the axial direction) to axial strains (when loaded along the axis) is called *Poisson's ratio* (named after the person who defined it in 1811). When a body is stretched in one direction, it contracts in the other perpendicular directions, and when it is compressed in one direction, it extends in the other directions.

Most materials of construction have a Poisson ratio in the range 0.15 to 0.40. Poisson's ratio for glass is 0.24, for steel is 0.28, and for granite is 0.25. For concrete Poisson's ratio lies between 0.1 and 0.18, depending on the mix proportions. Increase in cement content increases Poisson's ratio. The cement mortar has a Poisson ratio of about 0.16.

The change in the volume of a material is called *volumetric deformation.* Volumetric strain can be found as the ratio between the change in volume and initial volume. For a material subjected to axial force, the volumetric strain can be calculated by knowing the axial strain and Poisson's ratio.

$$\text{Change in volume} = l \times b \times d \times (1 - 2\mu)e'$$

where l, b, and d are dimensions of the member, μ is Poisson's ratio, and e' is the axial strain. (Note that the terms e'^2 and e'^3 are omitted in this derivation, as e' is a small quantity.)

$$\text{Volumetric strain} = \frac{lbd(1-2p_r)e'}{lbd}$$

$$= (1-2p_r)e'$$

By knowing the longitudinal or axial strain and Poisson's ratio, the volumetric strain or volumetric deformation can be calculated using the equation above.

1.2.3 Stiffness

Stiffness is a measure of the relative deformability of a material under load. A material that develops a high level of strain under a given stress is less stiff than is a material that has less strain when subjected to the same stress. In other words, the greater the stress needed to produce a known strain, the stiffer is the material. Steel is stiffer than cast iron, which is stiffer than concrete.

Stiffness of a material is measured in terms of its modulus of elasticity. *Elasticity* is that property of a material that enables it to change its length, volume, or form in direct response to the force applied, and to recover its original size or form when the load is completely removed. Some materials, such as steel and rubber, can endure a large amount of strain or deformation and still return to their original form. Concrete (in compression) is an example of a material that will recover its original size only when the applied stress is low.

The *elastic limit* is the maximum stress below which a material will fully recover its original form on removal of the applied forces. It is also defined as the greatest stress that can be applied without causing a permanent deformation. In concrete, brick, and stone, the elastic limit is low. But for most metals the elastic limit is high. To figure out the value of the elastic limit experimentally, we need to apply and release the load a number of times, load at each application being somewhat larger than the preceding one. This procedure is tedious and is not generally carried out. Instead, elastic limit is approximated as the proportional limit or yield point of the material.

The *proportional limit* is the maximum stress below which the ratio between stress and strain is constant. It is determined by plotting the stress-strain curve of the material in uniaxial tension or compression. Note that most materials exhibit the same elasticity in compression and tension.

Figure 1.5 shows two stress-strain curves, one for material A and the other for material B. Material A is stiffer than material 8. The ordinate of the graph represents the stress and the abscissa shows the strain. The basic procedure followed to draw the plot is to collect a series of extension or strain readings against data on load or stress. If load and extension (or contraction) are recorded, they can be converted to stress and strain by knowing the cross-sectional area and the gage length.

In both curves we note that the stress is linearly proportional to the strain up to a certain stress. The stress at which the plot deviates from the straight line is the proportional limit. If the material is loaded to any stress less than the proportional limit and then unloaded, the unloading plot follows pretty much the straight line of the loading plot. When the load is removed completely, the initial form is regained. Because of this, the proportional limit is generally used to mark the elastic limit of a material.

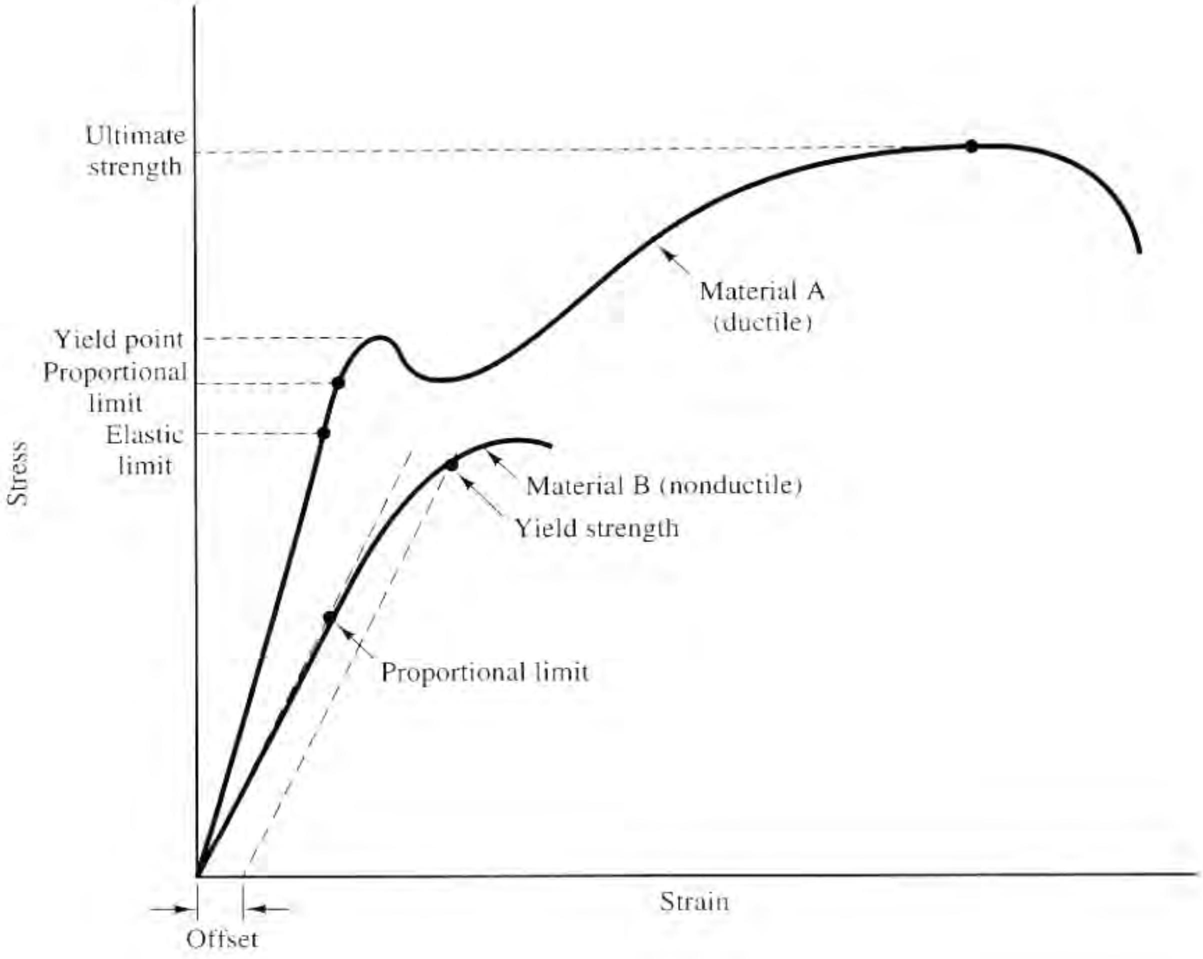


Figure 1.5 Stress-strain diagram.

But the exact point of departure of the curve from the straight line is difficult to determine, and for this reason, for most materials the elastic limit is taken as the yield point of the material. Note that a common meaning of the word *yield* is to concede under some pressure but not surrender totally (e.g., yielding mattress). Yielding in a material indicates, in a similar fashion, that the material is flexing a little but is not giving up completely. *Yield point* is the first unit stress at which deformation continues without an increase in load. For most materials the yield point is higher than the elastic limit and the proportional limit. In steel, this difference is about 5 to 15%.

Some materials, such as material B in Fig. 1.5, do not have a yield point. Metals such as copper, aluminum, and high-strength steel exhibit this type of property. The stress of strain curve deviates gradually from the initial straight line, and when the material is unloaded in this nonlinear portion of the curve, a permanent (nonrecoverable) deformation is found to exist in the material. This strain or deformation remaining in a previously stressed material, after it is unloaded, is called *set* or *permanent set.*

Jn materials that do not have a yield point, yielding and elastic limit are predicted using the permanent set or offset approach. The stress at which, upon removal of the load, the material displays a specified amount of offset is the *yield strength* of the material. Note that yield strength may not indicate yielding in the material at this stress; it is merely a convenient way for the measurement of a practical elastic limit.

In the offset method of yield strength prediction, a small value of offset is chosen, generally, based on recommended standards, between 0.1 and 0.3% (strain of 0.001 and 0.003). This offset is marked on the strain axis from the intersection of the stress-strain curve with the strain axis. Then a line is drawn from this offset point that is parallel to the initial straight-line part of the diagram (Fig. 1.5). The point of intersection of this line with the stress-strain curve is the yield strength.

The ratio of stress to corresponding strain below the proportional limit is called *modulus of elasticity* (also called as *elastic modulus* and *coefftcient of elasticity).* It refers to the stiffness in the elastic range and is generally identified using the letter E.

There are three moduli of elasticity, which correspond to three types of stress: tension, compression, and shear. These are modulus in tension, modulus in compression, and modulus in shear. The modulus of elasticity in tension or compression is also called *Young's modulus* (named after Thomas Young, who derived it). The modulus of elasticity of all grades of steel is about 29 x 10^6 psi (199,800 mpa) and that of structural aluminum is 10.5 x 10^6 psi (72,350 MPa). The modulus of elasticity of most construction materials (e.g., concrete, wood, and cast iron) is not constant.

The modulus of elasticity in tension or compression, Young's modulus,

$$E = \frac{f}{e'}$$

where f is the stress and e' is the strain. Since the shape of the stress-strain curve varies from material to material, there is more than one method to determine Young's modulus. The slope of a line drawn tangent to the stress-strain curve at the origin is the *initial tangent modulus* (Fig. 1.6). When the modulus is measured as the slope of a tangent drawn at specified stress f_s, it is called a *tangent modulus at stress* f_s - The *secant modulus* is the slope of a line connecting two points on the stress-strain curve.

It was indicated earlier that for most materials the moduli of elasticity in tension and compression are usually the same. The ratio between shear stress and shear strain is called the *modulus of elasticity in shear.* By comparing the shear deformation to the corresponding axial strain, it can be shown that the shear modulus is related to Young's modulus using the following relationship:

$$\text{shear modulus, £.} = \frac{E}{2(1 + Pr)}$$

where Pr is Poisson's ratio. It is difficult to determine the shear modulus experimentally, and thus the relationship above provides a convenient procedure to establish the shear modulus.

Ultimate strength is the maximum stress that can be applied to a material before it fractures. It is the highest point on the stress-strain curve. In some materials, such as steel and wrought iron, the cross section at fracture is much smaller than the original one.

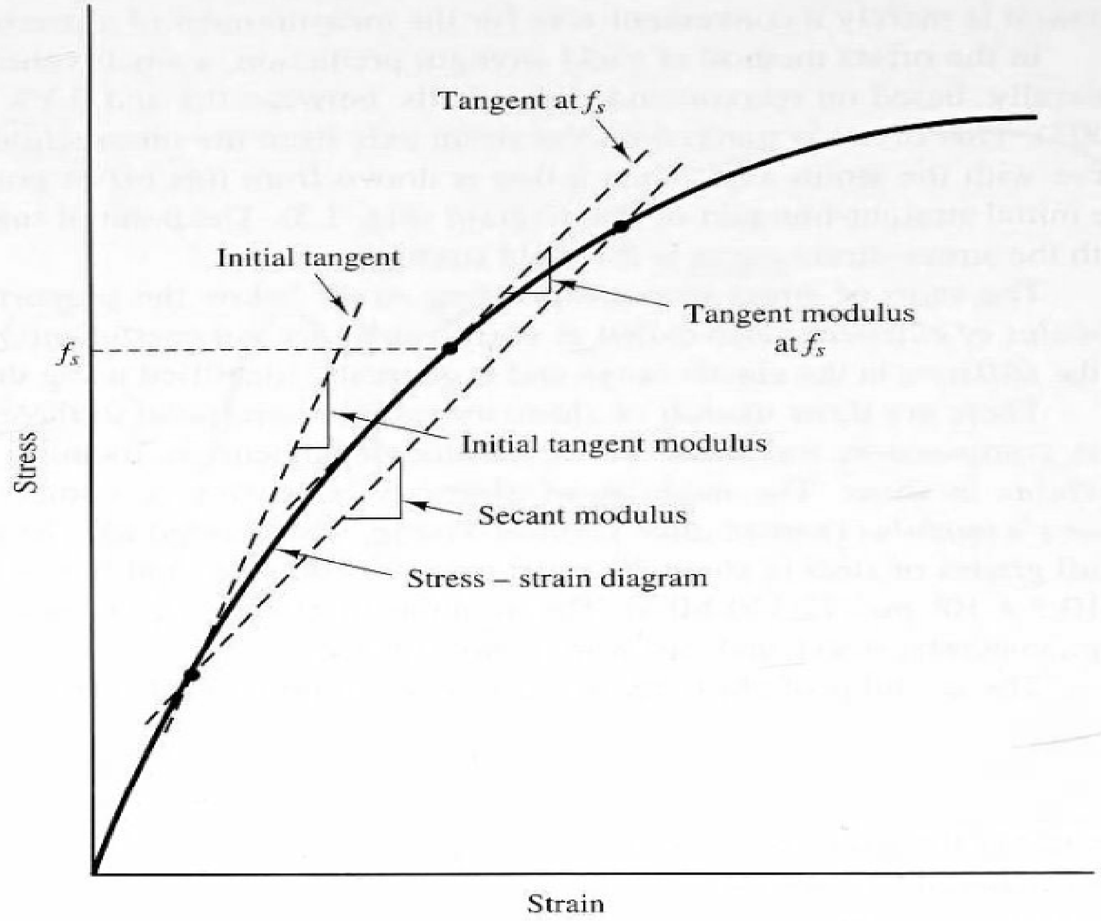


Figure 1.6 Modulus of elasticity.

1.2.4 Ductile and Brittle Materials

Plasticity is the property of a material that enables it to retain permanent set or deformation without fracture. It is thus the opposite of elasticity. (A common meaning of plasticity is the capability of being made to assume a desired form. Plastic clay is a material that has this property.) Plasticity is important in forming, shaping, and extruding procedures. In addition, plasticity shows a characteristic of a material that is important in predicting the type of failure in the material. Construction materials are generally divided into two classes:

- Plastic or ductile materials
- Brittle materials

When subjected to tensile loads, a *ductile* material is capable of undergoing a high level of plastic deformation before failure. Ductility is a property that allows the material to undergo change of form without breaking. Wrought iron, steel, and copper are some examples of ductile materials. These materials exhibit a large amount of deformation as an indication of eventual failure. Strong, ductile materials show higher levels of toughness than do brittle or soft materials, as shown in Fig. 1.7.

Toughness represents the ability of a material to support loads even after yielding or forming cracks. For most materials it is measured as the area under the load-deformation

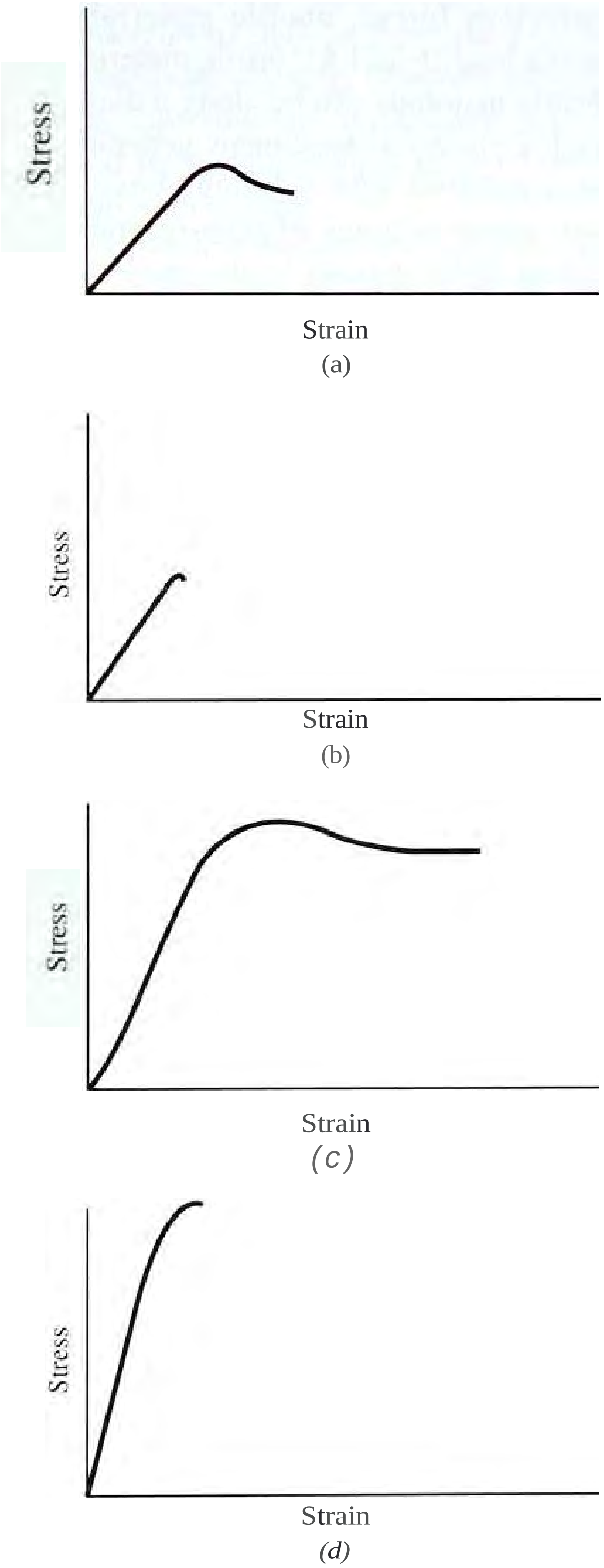


Figure 1.7 Stress-strain behavior of various materials: (a) soft and weak: (b) weak and brittle; (c) strong and tough; (d) strong and hard.

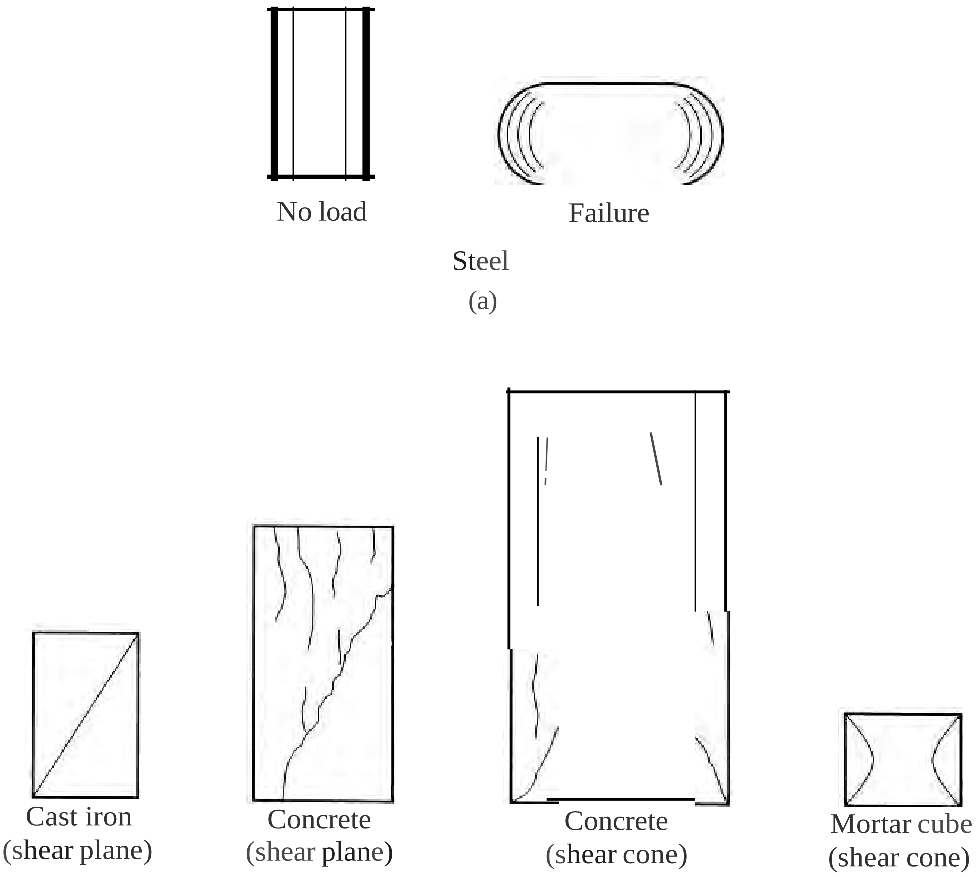
curve. An increase in toughness relates to an increase in the amount of energy needed to produce a specified damage condition.

Brittle materials have little or no plasticity or show little deformation beyond the elastic limit. Brittleness also expresses breakage with a comparatively smooth fracture (e.g., peanut brittle). In brittle materials failure is sudden and catastrophic. Some common brittle materials are cast iron, granite, brick, concrete, and glass. These materials, at failure, crush or crumble with very Little warning.

When subjected to compressive forces, ductile materials simply spread and increase in area under an increasing load (Fig. 1.8); brittle materials fail by shearing on certain angles. The rupture in brittle materials can be along a diagonal plane, or can be cone shaped or pyramidal shaped. Cylindrical specimens generally fail along a diagonal plane (e.g., cast iron) or as a pyramid with splitting above (e.g., concrete). The angle of rupture (called the *shear plane* or *plane of rupture)* measured from the horizontal depends on internal friction and cohesion in the material, and generally lies between 45 and 60°.

1.3 SELECTION OF MATERIALS

All primary materials of construction (i.e., structural materials) have to perform the following functions:



(b)

Figure 1.8 (a) Ductile and (b) brittle materials in compression.

- Carry the prescribed load.
- Satisfy serviceability requirements.
- Be aesthetically pleasing.
- Be practical economically.
- Be environmentally acceptable.

The most important requirement of a material used in civil engineering structures is that the material be able to carry the prescribed loads; in other words, the material should have adequate strength. Concrete used in a foundation should be able to carry the load from the superstructure and transfer it to the ground below without causing settlement. A wood beam supporting a timber floor should be strong enough to transfer this load to the supporting walls.

But as explained earlier, strength is a generic term that means different things in different applications. But no matter how the load is applied, all materials are required to carry it safely.

In addition to strength, all materials are required to satisfy serviceability requirements such as deformation limits, durability , performance characteristics, and adaptability. Typically, serviceability implies satisfactory performance at all times. Recorded data of performance in previous applications, laboratory test results, and established construction needs will help to assess the serviceability aspects of a material.

In general, a material should be able to satisfy all functional aspects pertaining to a specific job. For example, a material that leaves the surface slick and slippery when moist is a poor choice for paving roads. A mortar that loses its binding property and crumbles with time cannot be used in the construction of masonry walls. Lumber that deteriorates or is susceptible to termite attack cannot be used in an exposed environment. When selecting a combination of materials, the effects of the combination should be studied in terms of long-term performance.

Materials are sometimes selected based solely on appearance. Although most nonstructural materials such as floor coverings, paints, and doors and windows are chosen based on aesthetic requirements, the same demand also exists in some structural materials. The type of masonry for a public building may depend on how the finished surface looks. A concrete surface may be given different finishes based on architectural appeal. The material for exterior finish of a residential building (i.e., stucco, siding, etc.) may be based on the appearance.

In addition to these aspects described above, one of the major factors behind the choice of a material is invariably the cost or economical constraints. A typical residential building in the United States has walls, floor, and roof, all using wood or wood products. But the same building in Mexico, India, or Saudi Arabia is generally built using masonry walls, concrete floor, and concrete roof. The choice, in addition to some environmental factors, is based primarily on cost.

In all places, the selection of appropriate building materials is driven by economic constraints, which depend on local availability of material, on training, and on duration of construction. A typical shopping center in the United States may have masonry walls, tubular steel columns, and a wooden roof This type of construction, using various types of materials, combines the lightness of wood, the ductility and ease of erection of Steel, and the fire resistance of masonry. This leads to overall economy.

Environmental compatibility of a material is gaining importance in the selection. process. A construction material should satisfy all strength, serviceability, and architectural requirements, and at the same time, must not cause environmental problems. For example, a concrete pavement on a large parking space may cause flooding in adjacent land by forcing rainwater runoff, which makes the pavement incapable of maintaining the environmental balance. Cement dust produced from a batch plant or cement plant may be carried by wind and cause hazardous living conditions to adjacent residents. Finish materials in a building, such as carpets, floor coverings, and wall panels, may give out dangerous fumes in case of fire and cause hazardous conditions.

Consequently, pollution aspects of construction materials should be assessed in any situation, although most common materials of construction are known to be environmentally compatible. A flowchart that describes the steps in material selection is shown in Fig. 1.9.

1.4 STANDARDS

When we use a construction material in any civil engineering project, a number of questions come up. For example, if we are making concrete to anchor a fence post, a series of questions may include: What is concrete? Is there more than one type of concrete? How do we make concrete? What types of materials are available? How much water should be used? How much sand should be used? What do we do when the sand is wet? What should be done after the concrete is placed in the ground? Can the same concrete be used for other types of work, such as a sidewalk?

Finding answers to all these questions requires that one be proficient in all aspects of concrete manufacture, which translates to a thorough understanding of cement chemistry, geology, concrete behavior, the hydration process, and other factors. But even then, there is no guarantee that the concrete thus manufactured will be satisfactory, because of problems that may exist with cement that was purchased, bad aggregates in the vicinity, and many other practical reasons. To guarantee satisfactory performance from any material, all materials should satisfy a minimum of quality and product standards. In addition, the methods of application of these materials should follow standard procedures.

To bring in more uniformity in materials, methods of production, application, inspection, and testing, many organizations have developed standards for materials, testing, and inspection. Over the years these guidelines have gone through a number of revisions and been updated. In addition to these material standards, there exist specifications for application of various materials.

Standards represent efforts by organizations-private, government, or voluntary- to agree on a common procedure or goal. In the United States there are thousands of standards developed by various groups and recognized by many user agencies. The

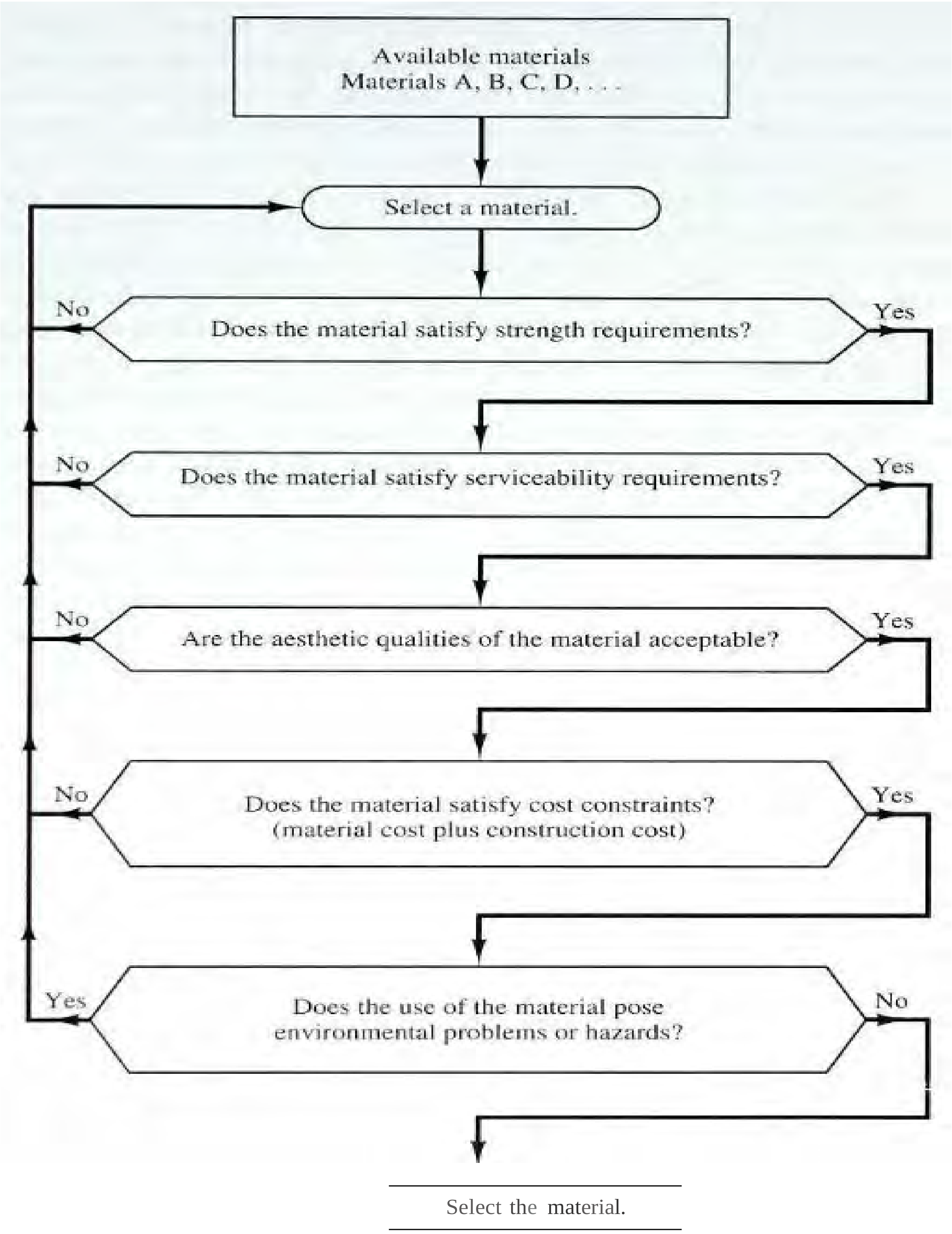

Available materials
Materials A, B, C, D, . . .
Select a material.
No
Does the material satisfy strength requirements?
Yes
No
Does the material satisfy serviceability requirements?
Yes
No
Are the aesthetic qualities of the material acceptable?
Yes
No
Does the material satisfy cost constraints? (material cost plus construction cost)
Yes
Yes
Does the use of the material pose environmental problems or hazards?
No
Select the material.

Figure 1.9 Materials selection flowchart.

American National Standards Institute (ANSI, 1430 Broadway, New York, NY 10018), National Forest Products Association (NFPA, 1619 Massachusetts Avenue N.W., Washington, DC 20036), Portland Cement Association (PCA, Old Orchard Road, Skokie, IL 60076), American Concrete Institute (ACI, P.O. Box 19150, Redford Station, Detroit, MI 48219), American Institute of Steel Construction (AISC, 400 N. Michigan

Avenue, Chicago, IL 60611), American Iron and Steel Institute (AISI, 1000 16th Street, N.W., Washington, DC 20036), and Brick Institute of America (BIA, 1750 Old Meadow Road, McLean, VA 22102) are some of the prominent organizations that are involved in the development of product and use standards for some common materials. In addition, most local county and city agencies, state agencies, defense organizations, and private user groups have developed independent standards and specifications.

The standards adopted by the American Society for Testing and Materials (ASTM, 1916 Race Street, Philadelphia, PA 19103; established in 1898) are of great importance to anyone interested in the use and testing of materials. A number of documents published by this society (referred to as ASTM standards or specifications in this book) deliver standards for materials and their testing. The material standards include definitions, formulation of materials specifications, and recommendations on construction practices. The testing standards show the development and description of testing procedures.

Where feasible, relevant ASTM Standards are referenced in this book. The testing procedures described at the end of each chapter are based solely on the recommendations of the ASTM but may not be the same. The purpose of narration in the book is neither to describe the ASTM techniques and specifications nor to duplicate their efforts. The aim of the book is to introduce many aspects of material specifications and testing to get an appreciation of the importance of knowing the material properties in the design and construction of safe and durable civil engineering structures. One is cautioned against using the procedures described for laboratory testing as described in the text to satisfy agency specifications; the book is not a substitute for ASTM standards or any other standards.

Many of the products that are available in the construction industry are manufactured to satisfy one or more pertinent ASTM Standards. By this we mean that by knowing the names or numbers of the standards or specifications, we can establish the chemical, physical, or other properties of materials that are marketed. For example, a clay brick that is said to be of grade SW (ASTM Standard Specification C62) can be expected to have been manufactured satisfying some physical requirements (such as minimum compressive strength) prescribed in the specifications. Consequently, we will be able to use this brick in any situation that matches the physical requirements of the brick without actually testing it. Thus, one could see that the standardization has helped us in choosing the right material in a given situation without the need for individual testing of any number of possible materials.

Even though the text refers to a number of product standards and testing procedures recommended in the ASTM Standards, as explained earlier, there are a large number of private and public agencies that write their own specifications. The use of a material in any project should be based on the specifications of the agency that runs the project. Their rules, procedures, and standards should be reviewed before one chooses a material.

CHAPTER 2

Aggregates

Aggregate is a rocklike material of various sizes and shapes used in the manufacture of portland cement concrete, bituminous concrete (asphalt concrete), plaster, grout, filter beds, railroad ballast, base course, foundation fill or subgrade, and so on. The ASTM (Cl25 and D8) defines aggregate as a granular material such as sand, gravel, crushed stone, or iron-blast-furnace slag used with a cementing medium to form mortar or concrete, or alone as in base course or railroad ballast. The size of aggregate particle ranges between that of dust and 2 in. (50.8 mm), and may be higher. Based on their sizes, aggregates are divided into two groups:

- Fine aggregate
- Coarse aggregate

Fine aggregate (also called *sand)* consists of natural or manufactured particles ranging in size from 0.006 in. (150 μ m) to ¾6in. (4.75 mm). In concrete construction the fine aggregate is defined as aggregate with predominant particles of size smaller than 3/16 in. (4.75 mm) and larger than 0.0029 in. (75 μm). *Coarse aggregate* consists of rounded river gravel, crushed stone, and manufactured aggregate of size larger than ½6 in. (4.75 mm). *Gravel* is naturally rounded aggregate larger than ¼ in. (6.35 mm), and *crushed gravel* is a fine aggregate made by crushing the gravel. Note that the size limit that separates a coarse from a fine aggregate is also dependent on the type of construction for which the aggregate is used. For example, aggregate larger than% in. (2.36 mm) is sometimes defined as coarse aggregate for use in asphaltic concrete construction.

When natural sand and gravel are not available, crushed stone or rock, which is a product resulting from quarrying and processing natural rocks, is used as fine and/or coarse aggregate. This type of aggregate is called *manufactured mineral aggregate.* Manufactured sand is produced by crushing stone, gravel, or air-cooled blast furnace slag, and is characterized by sharp, angular particles. Rocks, boulders, and similar materials are used as raw materials for the production of manufactured coarse aggregate, and the resulting particles are angular in shape. In addition, they are characterized by a rough surface texture, whereas rounded gravel has a very smooth texture. Note that sand, gravel, and manufactured mineral aggregate is also known collectively as *natural mineral aggregate.*

The rocks most commonly used in the manufacture of aggregate particles are granite, sandstone, and limestone. All three have high compressive strengths, in the range 13 to 34 ksi (90 to 235 MPa). Granite is hard, tough, and dense (specific gravity 2.6 to 2.7), whereas limestone and sandstone (specific gravity 2.0 to 2.6) range from hard to soft, heavy to light, and dense to porous. Both sandstone and limestone may contain clay, which renders these particles soft, friable, and absorptive. Limestones and sandstones with a crushing strength of less than about 14 ksi (100 MPa) may be unsuitable for the manufacture of concrete.

Aggregate can also be manufactured by crushing waste portland cement concrete and clay bricks, and these products can be an economical alternative when good-quality mineral aggregate is scarce. However, natural sand and gravel are by far the most common types of aggregate in construction and are used whenever they are of satisfactory quality and can be obtained economically in sufficient quantity.

2.1 LIGHTWEIGHT, NORMAL-WEIGHT, AND HEAVYWEIGHT AGGREGATES

Based on the specific gravity (or relative density) aggregates are divided into three types:

- Lightweight aggregates
- Normal-weight aggregates
- Heavyweight aggregates

Specific gravity is defined as the ratio of the mass of a unit volume of a material at a specific temperature to the mass of the same volume of gas-free distilled water at that temperature. Most natural mineral aggregates have specific gravities in the range 2.4 to 2.9 and bulk densities in the range 95 to 105 pcf, and fall into the normal-weight category. *Bulk density* (also called *specific weight)* is defined as the mass of a unit volume of an aggregate at a specified temperature and has the units of grams per milliliter, grams per cubic meter, pounds per cubic foot, or others. The unit volume is based on the volume occupied by the particles and the voids between them. Equations to calculate specific gravity and bulk density are derived in Section 2.2.2.

Gravel, crushed granite, and ordinary sand are all normal-weight aggregates. They are commonly used in the manufacture of normal-weight concrete, asphalt concrete, and roadway subbase. The average values of specific gravity for sand and granite are 2.6 and 2.65, respectively.

The ASTM Standards (C778) also identify a special type of sand called standard sand which comes in two grades: 20-30 sand and graded sand. The *standard sand* is a silica sand composed entirely of naturally rounded grains of nearly pure quartz quarried from Ottawa. Illinois, or LeSueus, Minnesota. The *20-30 sand* is predominantly graded to pass a No. 20 sieve and to be retained on a No. 30 sieve. A sieve is an apparatus with square openings for separating sizes of materials. The various sieve sizes available and sieve analysis are explained in Section 2.2.4. The *graded sand* is predominantly graded between No. 30 sieve and No. 100 sieve. *Slurry-seal sand* is a fine crushed sand that is mixed with liquid asphalt and applied in a thickness of *1/s* in. (3.2 mm) to fill cracks and irregularities in old asphalt concrete pavements. *Seal-coat aggregate* is an aggregate featuring very small, crushed rock particles that are mixed with liquid asphalt and applied over aggregate base and to resurface asphalt concrete or portland cement concrete.

Lightweight aggregate. The lightweight aggregate (any aggregate with bulk density less than 70 pcf or .1120 kg/m^3) is used as a raw material in the manufacture of lightweight concrete. It is also used in the production of lightweight masonry blocks to improve thermal, insulating, and nailing characteristics of these building materials. There are two types of lightweight aggregate:

- Natural lightweight aggregate
- Manufactured lightweight aggregate

Natural lightweight aggregate consists of particles derived from natural rocks, primarily those of volcanic origin. *Manufactured lightweight aggregate* is produced by expanding some raw materials in a rotary kiln, on a sintering grate, or by mixing them with water. The most common lightweight aggregates are pumice, scoria, expanded shale, expanded clay, expanded slate, expanded perlite, expanded slag, and vermiculite. Brief introductions to these materials are given in the following paragraphs.

Pumice (volcanic glass), the most widely used natural lightweight aggregate, is usually whitish gray to yellow in color but may also be brown, red, or black. It is found in large quantities in volcanic areas of the western United States and is porous in structure. It can be identified as a finely vesicular glassy rock containing tubular bubbles.

Scoria, which is also of volcanic origin, resembles industrial cinders and is usually red to black in color. (Cinders are residues from high-temperature combustion of coal in industrial furnaces.) The pores in scoria are larger than those of pumice and more or less spherical in shape.

Expanded perlite is an aggregate derived from crushing perlite ore and then expanding the resulting particles in a kiln by driving the water out. It is used to replace natural sand in lightweight concrete manufacture and has very good insulating properties. Concrete made with this aggregate has limited strength as well as high shrinkage. Perlite is also used in the manufacture of cement mortar.

Vermiculite, a type of mica, is also used in the manufacture of lightweight concrete. It is produced by heating the raw material until it expands up to 20 times its original volume. It is too soft and weak a material to be used in concrete that requires strength, but is used in plaster as a replacement for sand. The bulk density of vermiculite is in the range 4 to 12 pcf (64 to 192 kg/m^3), which is nearly the same as that of perlite. Concrete made with vermiculite or perlite has low compressive strength and high shrinkage, but excellent insulating properties.

Blast furnace slag is a nonmetallic product consisting essentially of silicates and aluminates of calcium (lime) and other bases that is developed in a molten condition simultaneously with iron in a blast furnace. *Expanded slag* is produced by expanding blast furnace slag mixed with water while still molten. The violent reaction between the molten slag and the water creates aggregate particles that are porous in structure. They are hard and possess considerable strength, but their use in structural concrete is limited because of their high sulfur content.

Expanded shale, clay, and *slate* aggregates belong in the manufactured lightweight aggregate category, and are produced by crushing the raw materials and heating them to the fusion point [approximately 2460° F (1350° C)J, when they become soft and expand (up to 600 to 700% of original volume) because of entrapped gases. They are also produced by sintering, a process in which a mixture of raw materials, including coal or ashes, in moving grates is exposed to flames under forced draft. The resulting product is then crushed to the sizes desired.

Some lightweight aggregates are also used to manufacture *nailable concrete.* Sawdust, expanded slag, pumice, and scoria are some of the most commonly used aggregates in the production of this type of concrete. It is made by mixing cement, sand, and sawdust or other lightweight aggregates with sufficient water. When sawdust is used it should have particles of size¾ to ½2 in. (19 to 2.5 mm), be free of tannic acid, and contain very low amounts of bark. (Note that tannic acid or tannin and sugar will retard the setting of cement.) Pine and Fir sawdust, which contain little or no tannin, are good aggregates. Various methods of processing sawdust include pretreatment with lime and calcium chloride, aging for periods up to one year, and presoaking for 5 minutes to 24 hours and washing. This processing period is usually followed by a drying period. Most of the softwood sawdust can be rendered compatible with the cement if a mixture of lime and cement is used as the binder.

Sawdust concrete is used for floor finishes and in the manufacture of precast floor tiles. Sawdust concrete made with a 1:3 mix of cement and sawdust by volume and enough water to produce good workability may be expected to have a density of 55 pcf (880 kg/m^3) and compressive strength of as high as 700 psi (4.8 MPa), which can be increased by increasing the cement content.

Bulk density of various lightweight aggregates range from 10 to 70 pcf (160 to 1120 kg/m^3), but most have values below 50 pcf (800 kg/m^3). Expanded perlite (which is used in the manufacture of insulating concrete) has an average bulk density of 15 pcf

(240 kg/m^3), pumice has about 30 pcf (480 kg/m^3) and expanded clay, slate, and shale all have about 50 pcf (800 kg/m^3).

Heavyweight aggregate. *Heavyweight aggregate* is an aggregate of high density that is used primarily to manufacture heavyweight concrete for protection against nuclear radiation. Heavyweight concrete varies in unit weight from 150 pcf or 2400 kg/m^3 (using normal-weight aggregates) to 400 pcf or 6400 kg/m^3 (containing steel punchings as coarse and fine aggregates).

A number of naturally occurring materials such as mineral ores and barite (also called heavyspar) have been used for the manufacture of heavyweight concrete. Barite is a quarry rock with a high barium sulfate content (90 to 95%), a small percentage of iron oxide, and some crystalline rocks. It has a specific gravity in the range 4 to 4.6 and an average bulk density of 150 pcf (2400 kg/m^3). Some iron ores, such as limonite and magnetite, are used as fine and coarse aggregates after processing. They have specific gravity in the range 4.1 to 5.2, an average bulk density of 180 pcf (2880 kg/m^3), and are used to produce concrete of unit weight in the range 210 to 260 pcf (3360 to 4160 kg/m^3). Manufactured iron products are used to make extra-heavyweight concrete (of density around 300 pcf or 4800 kg/m^3). Steel punchings, steel bars, and steel shot have specific gravities between 6.2 and 7.7 and may be more expensive than natural heavyweight aggregate.

The specific gravity values of some of the more commonly used aggregates are shown in Table 2.1. Note that individual aggregates, when tested, may present values that do not match those listed in the table, due to variations in the mineral constituents in the rocks.

2.2 PROPERTIES OF AGGREGATES

A number of physical and mechanical properties affect durability, strength, and performance of construction products manufactured using aggregates. The aggregate particles should retain their strength, shape, and texture when used with materials such as cement and asphalt. The most important properties to consider in selecting an aggregate for a particular application are its:

- Specific gravity
- Bulk density
- Porosity
- Voids
- Absorption
- Modulus of elasticity
- Moisture content
- Shrinkage
- Gradation and fineness modulus
- Chemical reactivity
- Compressive strength

TABLE 2.1 AGGREGATES: TYPES AND SPECIFIC GRAVITY

Aggregate	Type	Average specific gravity
Granite	Normal weight, mineral	2.6,5
Gravel	Normal weight	2.70
Limestone	Normal weight, mineral	2.65
Perlite	Lightweight, Natural	2.50
Pumice	Lightweight, Natural	0.75
Quartzite	Normal weight, mineral	2.69
Scoria	Lightweight, natural	0.75
Expanded shale, clay, and slate	Lightweight, manufactured	1.0
Sawdust	Lightweight, organic	0.5
Expanded vermiculite	Lightweight, manufactured	0.2
Expanded perlite	Lightweight, manufactured	0.75
Sand	Normal weight	2.60
Barite	Heavyweight	4.50

A brief description of some of these properties is presented in the following section.

2.2.1 Specific Gravity and Moisture Content

Specific gravity is the ratio of the mass of a unit volume of a material at a specific temperature to the mass of the same volume of gas-free distilled water at that temperature. Since aggregate particles contain pores, the volume of particles remains a function of the method of measurement of volume. The weight of aggregate particles, on the other hand, depends on the moisture level. As a result, the specific gravity readings should be associated with the moisture level or moisture content measurement. Two types of moisture measurement are recognized in aggregate particles:

- Absorbed moisture
- Surface moisture.

Water absorption or *absorbed moisture* is defined as the weight of water absorbed by dry aggregate particles in reaching the saturated surface dry condition. It is usually expressed as a percentage of dry weight. In this state there is no water on the surface of a particle, but all the pores are filled with water. A particle will neither absorb moisture from nor contribute moisture to the surrounding. Absorption is also defined as the increase in weight of aggregate due to water in the pores but not including water adhering to the outside surface of the particle. Moisture that is in excess of absorbed moisture is the surface moisture.

Absorption is commonly expressed as a percent of the weight of dry aggregate. Granite has a very low absorption value (less than 1%) and porous sandstone has a very high absorption value (as high as 13%). Lightweight aggregate has a high absorption value. generally in the range 5 to 20%.

Total moisture content (MC) is found by determining the loss in weight of a representative 1000-g sample of sand or 2000-g of coarse aggregate after it has been dried to a constant weight. The free moisture or surface moisture is obtained as total moisture minus absorbed moisture (saturated surface dry condition). Moisture may also be retained in the particles as chemically bound to the atomic structure which is called *adsorbed moisture.* Equations to determine moisture content, absorption, and surface moisture are given below.

$$\text{Total MC} = \frac{\text{original sample wt} - \text{oven-dry wt}}{\text{oven-dry wt}} \times 100$$

$$\text{Absorption} = \frac{\text{saturated surface dry wt} - \text{oven-dry wt}}{\text{oven-dry wt}} \times 100$$

$$\text{Surface MC} = \text{total MC} - \text{absorption}$$

Surface moisture in sand can cause considerable bulking. *Bulking* is the increase in volume over dry-rodded sand volume caused by pulling apart of the particles due to surface tension. The percent increase -in volume, or bulking, depends on the moisture content and the size of aggregate particles, as shown in Fig. 2.1. It is highest for fine sands

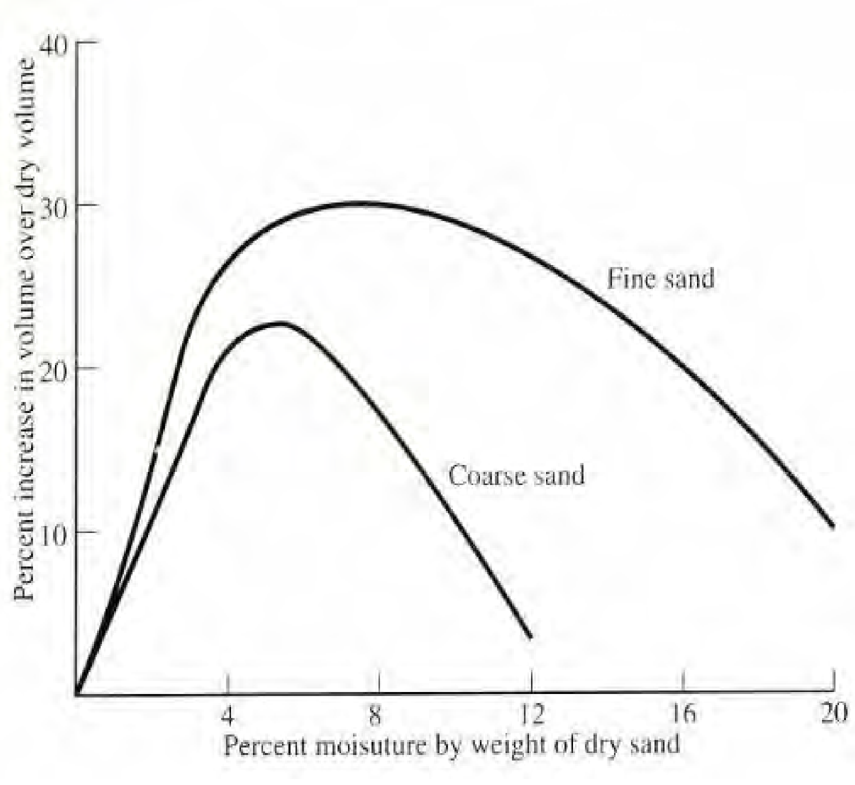


Figure 2.1 Effect of moisture on voids in sand (bulking).

(about 35%) and lowest for coarse sands (about 15%). The moisture content that causes maximum bulking is around 5%.

In general the moisture condition of aggregate is divided into four states (Fig. 2.2):

- Oven dry
- Air dry
- Saturated surface dry
- **Wet**

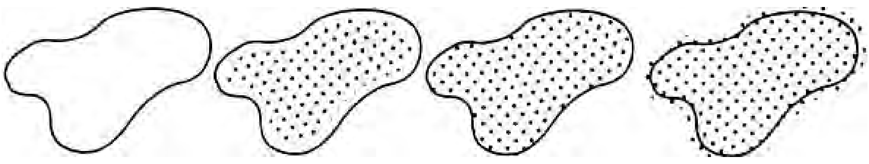
The state of moisture condition when all pores in the particles are filled with water but no moisture exists on the outside surface is called the *saturated surface dry condition.* When the amount of moisture in the particles is less than that for the saturated surface dry condition but more than that which remains in the oven-dry condition, the aggregate is referred to as *air dry*. Air-dry particles are somewhat absorbent. An *oven-dry* condition is obtained when all the moisture is driven out of the pores by drying the aggregate to a constant weight at a temperature of about 110°C (230° F). A *wet* condition exists when excess moisture (free water or surface moisture) remains on the surface of the particles, as in sand exposed to rainwater.

As mentioned earlier, the specific gravity of aggregate can be defined in different ways, due to the existence of pores in the particles and the associated moisture level. *Bulk specific gravity* (Bulk SG) is the ratio of the weight in air of a unit volume of a permeable material (including both permeable and impermeable pores) at a specific temperature to the weight in air of an equal volume of gas-free distilled water at that temperature. When the weight in air includes the weight of water within the pores, the bulk specific gravity is for saturated surface condition.

Apparent specific gravity (Apparent SG) is the ratio of the weight in air of a unit volume (that of the impermeable portion) of a material at a specific temperature to the weight in air of an equal volume of gas-free distilled water at that temperature. It pertains to the relative density of the solid material making up the constituent particles without including the pore space within the particles that is accessible to water.

$$\text{Bulk SG} = \frac{\text{density of aggregate based on solid plus pore volume}}{\text{density of water}}$$

$$\text{Apparent SG} = \frac{\text{density of aggregate based on solid volume (without permeable voids)}}{\text{density of water}}$$



Oven dry Air dry Saturated Wet

Figure 2.2 Moisture condition of aggregate.

When the density of aggregate is based on saturated particles, specific gravity is said to be at saturated surface dry condition. Similarly, when the density is based on the weight of oven-dry particles, the specific gravity is said to be in oven-dry condition.

Bulk specific gravity of aggregate is commonly expressed for the saturated surface dry condition. In the manufacture of cement concrete and asphalt concrete it is the bulk specific gravity that is of interest, and as a result the term *specific gravity* is often used instead of *bulk specific gravity*. It was indicated earlier (Table 2.1) that specific gravity of normal-weight aggregate is anywhere between 2.55 and 2.75, with 2.65 being common for granite. Apparent specific gravity is not widely used in construction technology.

2.2.2 Bulk Density and Voids

Unit weight or *bulk density* (also called *dry-rodded weight* and *specific weight)* is the mass per unit volume of aggregate. The mass is determined in dry condition, and the volume includes the volume of voids. The unit weight is measured by filling a standard container with the representative sample of the aggregate and recording the weight of the material in the container. The volume measurement (container volume) includes a volume of voids between the particles. For normal-weight aggregates the bulk density ranges between 95 and 105 pcf (1520 to 1680 kg/m^3), and for lightweight aggregates it is between 10 and 70 pcf (160 and 1120 kg/m^3). Heavyweight aggregates have bulk density values exceeding 150 pcf (2400 kg/m^3).The unit weight of aggregate is needed in designing concrete mix proportions. By knowing the unit weight of an aggregate it is possible to predict the density of concrete made with it.

Voids represent the amount of air space in the aggregate or space between the particles. Void content is generally expressed as a percent of gross volume which is solid volume plus volume of voids. For example, 40% void means that the solids occupy 60% of the volume of the aggregate, and 40% of the volume is filled with air (assuming that the aggregates are dry). For any aggregate, void content can be determined by knowing its specific gravity and bulk density using the equation

$$\text{void (\%)} = \frac{SG \times W - B}{SG \times W} \times 100$$

where SG is the specific gravity, W the density of water, and B the bulk density.

Void content in normal aggregates ranges between 30 and 50%. In concrete mixes the void content in the mixed aggregate should be as low as possible. In mixed aggregates containing about 40% sand and 60% gravel, the void content can be as low as about 25%. A good mixture of concrete has about 75% of its volume occupied by mixed aggregates, and the balance is made up of cement paste and air voids.

Porosity is defined as the ratio of the volume of the pores in a particle to its total volume (solid volume plus the pore volume):

$$\text{porosity} = \frac{\text{volume of pores}}{\text{total volume}}$$

Most granites and limestones have very low porosity (about 1%), whereas the majority of sandstones generally have a slightly higher porosity (about 3%). The porosity of a few types of limestones and sandstones may be as high as 13% and 30%, respectively.

The porosity of aggregate particle and the character of the pores affect its freezing characteristics. Freezing occurs when pores are filled with water and the ambient temperature drops. A porous stone is less resistant to freezing than is a stone of dense crystalline structure. Stones whose pores are connected by small tubes are more greatly weakened by freezing than are stones that have large pores and larger connecting tubes.

Strength, water absorption, and permeability of the aggregate are affected by the porosity and thus affect the behavior of both freshly mixed and hardened concrete. When concrete is used in cold climates, its resistance to freezing and thawing is important, as without it the concrete will disintegrate. Resistance is related to a number of variables, including aggregate porosity, absorption, and pore structure. If a porous aggregate particle absorbs so much water that the remaining pore space available is insufficient to accommodate the expansion of water that occurs during freezing, the particle may fail. The failure depends on the size of the particle and its tensile strength. Granite possesses excellent resistance to freeze-thaw cycles. Sandstone and limestone also have good resistance but perhaps not as great as that of granite.

2.2.3 Modulus of Elasticity and Strength

The *modulus of elasticity* is the ratio of stress to corresponding strain below the proportional limit. For granites and limestones, the modulus of elasticity in compression is in the range 2 x 10^6 to 7 x 10^6 psi (13.8 x 10^3 to 48.3 x 10^3 MPa). Sandstone generally has a lower value of modulus, which may range from 1 x 10^6 to 5 x 10^6 psi (6.9 x 10^3 to 34.5 x 10^3 MPa). The modulus of elasticity of concrete increases with increase in the modulus of aggregate used in its manufacture. Creep and shrinkage of concrete are also affected by the modulus of elasticity of the aggregate.

Modulus of elasticity and deformation characteristics of aggregates are seldom considered in studying the suitability of a type of aggregate for a particular use. Rocks, typically, do not obey Hooke's law, although granite, limestone, and a few others exhibit stress-strain relationships that are nearly elastic. Sandstone, which has a porous texture, exhibits nonlinear stress-strain relationship at very small stresses.

Compressive strengths of aggregates depend on the compressive strengths of original rocks. Granites and limestones have high compressive strengths, and sandstones and lightweight aggregates have low compressive strengths. Typically, limestone and granite have an average low compressive strength of 13,000 psi (90 MPa), whereas sandstone has an average low compressive strength of 6000 psi (40 MPa). Basalt has a very high compressive strength, generally around 23,000 psi (160 MPa). The flexural strength of basalt is also very high, about 5000 psi (35 MPa). Granite and limestone have a flexural strength close to 2200 psi (15 MPa).

The *strength* of an aggregate affects the strength of the building material made with it when the two strength values are close to each other. Generally, the compressive strength of aggregate is much higher than that of concrete made with the aggregate, which means that the latter .is unaffected by variations in the former. For example, the compressive strength of granite may range from 15,000 to 30,000 psi (100 to 200 MPa). Granite aggregate is used to make concrete with an average compressive strength of 4000 psi (27.5 MPa), which is substantially lower than the minimum compressive strength of the aggregate.

Thus it can be concluded that the strength of concrete made with granite aggregate is independent of the compressive strength of granite. However, when the aggregate chosen for a building product, such as concrete, has very low compressive strength (as in the case of some lightweight aggregates), the resulting product may not satisfy the strength requirement for that product.

2.2.4 Gradation

Gradation (also called *grain-size distribution)* refers to the proportions (by mass) of aggregate distributed in specified particle-size ranges. It is an important property that affects mix proportions, workability, economy, porosity, durability, and shrinkage of the finished product. Aggregates conforming to the specified grading limits produce a mix with the lowest void content and thus require the least binder material (e.g., cement) (Fig. 2.3).

Grading refers to the process that determines the particle-size distribution of a representative sample of the aggregate. The process of combining aggregates of various sizes to obtain a specified gradation is called *blending.*

A *graded aggregate* is one that conforms to the specified grading limits of the material specifications. A *dense-graded aggregate* is one that has a particle size distribution such that when it is compacted, the resulting voids between aggregate particles,

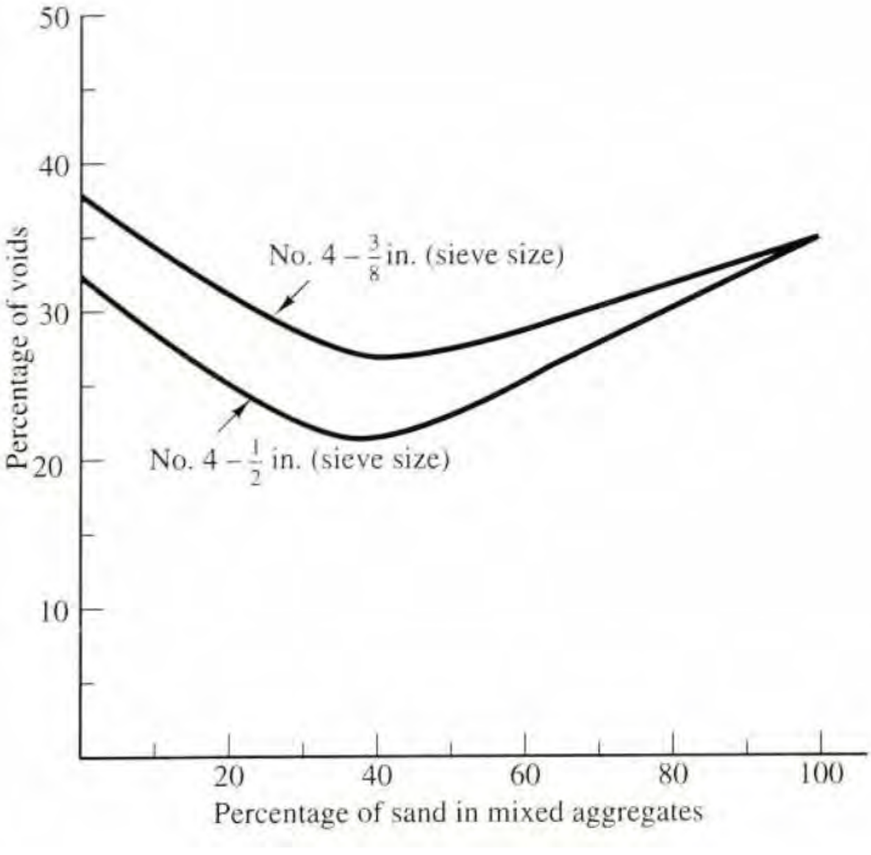


Figure 2.3 Variation in the volume of voids for various sand–gravel mixtures.

expressed as a percentage of the total space occupied by the material, are relatively small. An *open-graded aggregate* is one that bas a particle-size distribution such that when it is compacted, the voids between the aggregate particles, expressed as a percentage of the total space occupied by the material, remain relatively large.

In designing a concrete mix a constant goal is to achieve maximum density with minimum amount of paste to attain the desired quality. A properly graded aggregate is important in accomplishing this goal. Particle-size distribution of aggregates or the gradation will have an impact on the workability of the mix, finish characteristics of concrete, quantity of cement used, and cost, density, and strength of the product.

Gradation is determined using sieve analysis in which a representative sample of the aggregate is passed through a series of sieves and the weight retained in each sieve (expressed as a percent of the sample weight) is compared with the grading limits required.

A *sieve* is an apparatus with square openings. Some sieves are identified by their opening sizes and the others by numbers. Standard coarse aggregate sieves are No. 4, ¾ in., ½in., ¾ in., 1 in., 1½in., 2 in., and 2½ in., Standard fine aggregate sieves are No. 100, No. 50, No. 30, No. 16, No. 8, and No. 4. The opening sizes of these sieves are shown in Table 2.2. It can be seen from the table that the sieves are arranged so that most sieves

TABLE 2.2 SIEVE SIZES

Sieve designation		Normal opening		
in.	mm	in.	mm	Type[a]
2	50	2	50	H
I½	37.5	1.5	37.5	F
	25	I	25	H
¾	19	0.75	19	F
½	12.5	0.5	12.5	H
¾	9.5	0.375	9.5	F
No. 4	4.75	0.187	4.75	F
No. 8	2.36	0.0937	2.36	F
No. 16	1.18	0.0469	1.18	F
No. 30	600 µm	0.0234	0.60	F
No. 50	300 µm	0.0117	0.30	F
No. 100	150 µm	0.0059	0.15	F
No. 200	75 µm	0.0030	0.075	F

[a] H; half sieve; F; full sieve.

have openings that are one-half the opening of the higher sieve. These sieves are called *full sieves;* the others are called *half sieves.*

As cited earlier, sieve analysis or mechanical analysis consists of determining the proportionate amounts of particles retained on or passing through a series of sieves of decreasing size. Using percentages of weights retained in each sieve, a plot is drawn called a *particle-size distribution. curve.* From the plot it is possible to determine if the particles are properly graded to produce minimum voids and to satisfy grading limits. In addition, using the chart it is possible to study how the aggregate sample may be improved to make it satisfy the grading requirements.

The sieve analysis of fine aggregate is carried out in a mechanical shaker that is designed for 8-in. (203-mm) diameter standard sieves, and that of coarse aggregate may be completed using sieves mounted in frames larger than the standard 8-in. (203-mm)-diameter frames. The mechanical shaker will impart a vertical or lateral and vertical motion to the sieve, causing the particles thereon to bounce and turn so as to present different orientations to the sieving surface. The sample is placed on the top sieve, and the set of sieves is agitated in the shaker. By knowing the weight of particles retained in each sieve, the percentages of weight passing (finer than) or retained (coarser than) are calculated. These values are then compared with the allowable limits or standard limits to show if the sample is acceptable.

Typical limits for standard aggregates for concrete and road construction are shown in Tables 2.3 and 2.4. The grading requirements of fine aggregate for use in masonry mortar (natural sand and crushed stone) are given in Table 2.5.

The results from the sieve analysis are often represented in a gradation chart as shown in Figs. 2.4 and 2.5. In these figures the percentages finer than or coarser than are plotted as ordinates and the size of openings as abscissas. The latter is normally represented on a log scale. If the gradation chart of an aggregate sample falls within the two limits for the standard aggregate, the sample is said to satisfy the specifications or standards.

In addition to a graphical representation of grading distribution the sieve analysis is used to determine a factor called a fineness modulus. A *fineness modulus* is a number obtained by adding the percentages of material in the sample that is coarser than each of the following sieves (cumulative percentages retained) and dividing the sum by 100: No. 100, No. 50, No. 30, No. 16, No. 8, No. 4, ¾in.,¾ in., 1 ½ in., 3 in., and 6 in.

Compared with the grading chart, fineness modulus is less informative but is useful in measuring the average particle size of the sample. The average size of the sample is found as the size of the *nth* sieve counted from the last sieve in the set. For example, a fineness modulus of 3.0 using a set of sieves starting from No. 4 to No. 100 indicates that the average size of the sample is the third sieve from the bottom, which is No. 30. A smaller number or smaller modulus indicates a larger portion of finer particles (or fine sand) and a higher number indicates a larger portion of coarser particles (or coarse sand). Very fine aggregate with a fineness modulus within the range 1.0 to 1.7 is called *blend sand.* It is used in concrete to improve workability, pumpability, and finishing characteristics.

In concrete manufacture fineness modulus of sand may lie between 2.2 and 3.2. The lower number shows fine sand and the higher number displays coarse sand. Example

TABLE 2.3 TYPICAL STANDARD AGGREGATES

Normal size	Amounts finer than each sieve(%)									
	I in.	¾ in.	½ in.	¾ in.	No. 4	No. 8	No.16	No. 30	No. 50	No. 100
Size of Aggregate for Road and Bridge Construction (ASTMD448)										
I in. to No. 4	95-100		25-60		0-10	0-5				
½in.to No. 4			90-100	40-70	0-15	0-5				
No.4 to 0					85-100					10-30
Size of Aggregate for Concrete (ASTM C33)										
J in. to No. 4	95-100		25-60		0-10	0-5				
½in.to No. 4			90-100	40-70	0-15	0-5				
Fine aggregate					95-100	80-100	50-85	25-60	10-30	2-10

Source: ASTM C33 and .0448.

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TABLE 2.4 GRADING REQUIREMENTS FOR VARIOUS TYPES OF SAND

Type of sand	Percent passing sieve No.:							
	4	8	1.6	20	30	40	50	100
20-30 Sand			100	85-100	0-5			
Graded sand			100		96-100	65-75	20-30	0-4
Sand for concrete	95-100	80-IOO	50-85		25-60		10-30	2-10

TABLE 2.5 GRADING REQUIREMENTS OF FINE AGGREGATES FOR MASONRY MORTAR.

Sieve size	Opening	Percent passing Natural sand	Percent passing Manufactured sand
4	4.75 mm	100	100
8	2.36 mm	95-100	95-100
16	1.18mm	70-100	70-100
30	600µm	40-75	40-75
50	300µm	10-35	20-40
100	L50 µm	2-L5	10-25
200	75µm		0-10

Source: ASTM Cl44.
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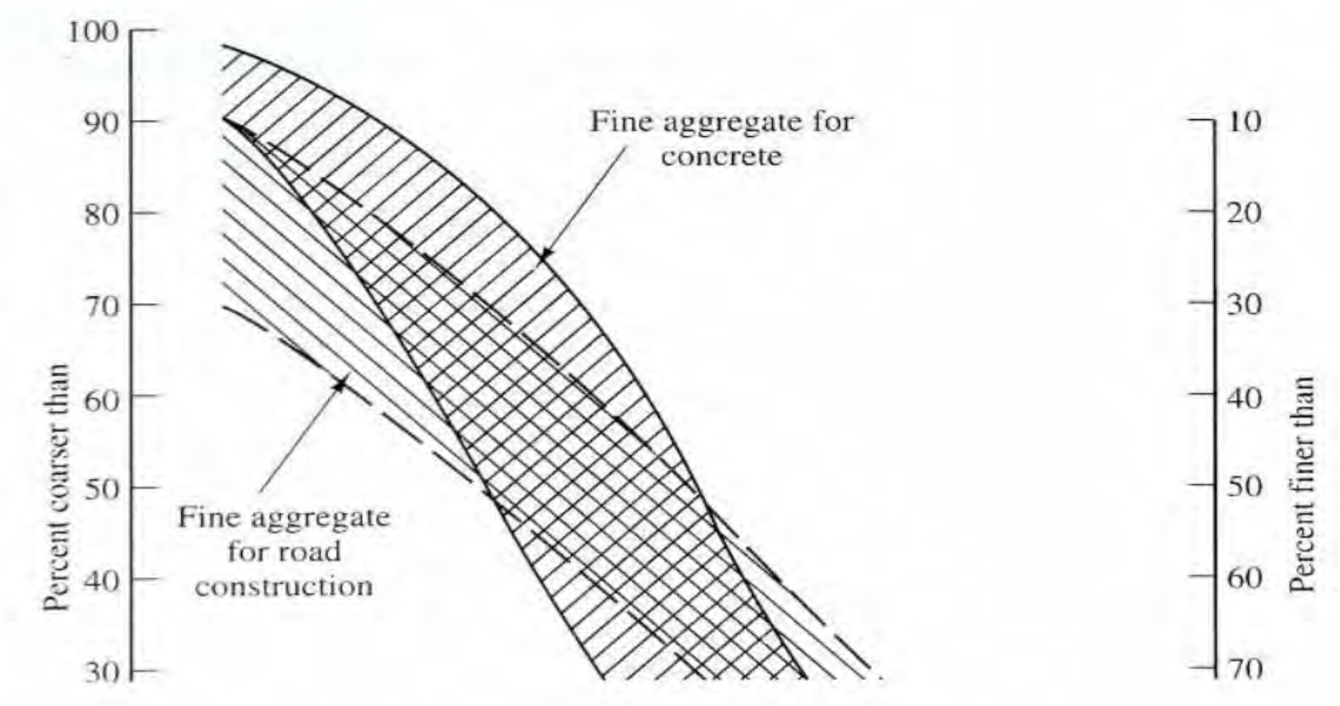


Figure 2.4 Standard specifications of fine aggregate for concrete and road and bridge construction. (From ASTM C33 and D448. Copyright ASTM. Reprinted with permission.)

2.1 (see Section 2.2.6) illustrates the procedure for plotting the grading distribution and calculating the fineness modulus.

2.2.5 Other Properties

Specific gravity, moisture content, bulk density, voids, porosity, modulus of elasticity, compressive strength, and gradation were described earlier. Most of these properties are routinely measured and used in mix design calculations. A few other properties that are useful in concrete and highway construction are discussed in the following sections.

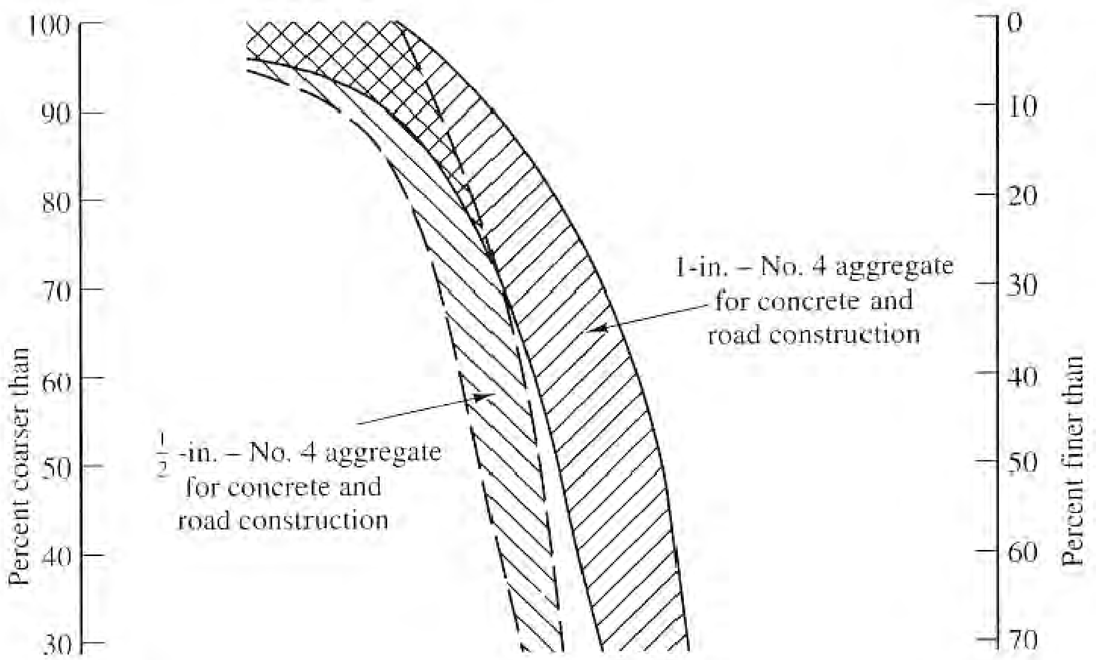


Figure 2.5 Standard specifications of coarse aggregate for concrete and road and bridge construction. (From ASTM D448 and C33. Copyright ASTM. Reprinted with permission.)

The *abrasion resistance, wear resistance,* or *hardness* is an important property in determining the suitability of an aggregate for use in roads and pavements. Abrasion is the mechanical wearing and scraping of rock surfaces by friction or impact or both. Hardness is a measure of the resistance of a material to deformation indentation or scratching.

The abrasion resistance of aggregate is important when used in concrete and other products that are subject to abrasion, as in heavy-duty floors or pavements. But it should be pointed out that the abrasion resistance of aggregate is not directly related to that of the building material made with the aggregate. Abrasion resistance is measured by the LA Abrasion Test (ASTM Cl3 l). This test ("Test method for resistance to degradation of small-size coarse aggregates by abrasion and impact in the Los Angeles Machine," developed in 1916) is both an impact and an abrasion test. When more than 50% abrasion losses are encountered in the test, the aggregates may not perform well in construction. The abrasion resistance value of sandstone, limestone, and granite are nearly equal to each other.

Toughness is a measure of resistance to fracture under an applied load. There is no satisfactory test for measuring effective strength and toughness of aggregates. Resistance of aggregate to failure by impact is commonly taken as a measure of toughness. Impact resistance shows the strength of aggregate to vibratory force or similar shock loads. Toughness is linearly related to its compressive strength.

Aggregates must be tough enough to support the weight of the rollers during the construction of a pavement and the repeated impact and crushing action of the traffic. Limestone exhibits somewhat lower toughness characteristics than those of sandstone or granite.

As a rule, aggregates for use in concrete and highway construction must be clean, hard, strong, and durable. They should be free of chemicals and fine material coatings.

which may affect their performance and bonding characteristics. Aggregates that are prone to split and crack during handling and transportation should be avoided. Materials on the surface of aggregate particles such as silt and clay lower the bond characteristics of particles.

Extremely fine fractions of aggregate particles-particles passing No. 200 sieve (75 µm), are commonly called *silt* and should not be permitted in large amounts. Silt is mostly nonplastic. It has little or no strength when air dried. When present in considerable amounts silt can increase the water requirements of concrete mix. This, in turn, contributes to decreased strength and durability. However, very fine grained silicious materials (such as ground pumice) are sometimes added to the aggregate mix to increase workability, strength, and durability through pozzolanic action.

Some aggregates may contain appreciable amounts of shale, organic matter, expansive material, and soft or porous particles which make them unfit for use. These harmful materials are called *deleterious materials.*

A visual inspection of coarse aggregate will often reveal the presence of such deleterious materials. However, it *is* not easy to inspect the fine aggregate in the same way, and standard tests may be carried out to determine the amount of impurities. ASTM C40-84 describes the standard test procedure for an approximate determination of the presence of injurious organic compounds in fine aggregate. Most of the deleterious materials can be removed by washing or flushing with water.

Aggregates or some compounds in them are known to react with other materials of construction chemically and are deleterious. For example, certain substances in limestone and dolomite aggregates (reactive silica) are known to react with cement (particularly in a warm, moist environment), which may cause deterioration of concrete made with them. The type of reaction is referred to as an *alkali-aggregate reaction* because of the chemical reaction of the silica in aggregates with the alkalies present in the cement (primarily sodium hydroxide and potassium hydroxide). The type of reaction is characterized by maplike cracks in the concrete.

These cracks will weaken the concrete and allow moisture to penetrate (see also Section 3.7.5). The action of other deleterious aggregate particles with cement may slow the hydration process and result in harmful by-products. [t should be noted that ordinary aggregates possess chemical stability in concrete (which means that the particles do not undergo chemical changes) and do not react with cement.

2.2.6 Examples

Example 2.1

Sieve analysis of a 1000-g sample of fine aggregate resulted in the following data. Find the fineness modulus.

Sieve size	4	8	16	30	50	100
Weight retained (g)	26	130	240	252	210	138

Solution

Sieve No.	Weight retained (g)	Percent retained	Percent coarser	Percent finer
4	26	2.6	2.6	97.4
8	130	13.0	15.6	84.4
16	240	24.0	39.6	60.4
30	252	25.2	64.8	35.2
50	210	21.0	85.8	14.2
JOO	138	13.8	99.6	0.4
		Cumulative:	308.0	

$$\text{Fineness modulus} = \frac{308}{100} = 3.08$$

Average sieve size = third sieve from the bottom

= No. 30 = 0.0234 in.

Example 2.2

Find the volume of voids in a 3-yd^3 coarse aggregate of bulk density equal to 102 pcf. The specific gravity of the particles is 2.65.

Solution

$$\text{Void} = \frac{SG\text{x } W-B}{SGxW} \times 100$$

Specific gravity, SG = 2.65

Density of water, W = 62.4 pcf

Bulk density, B = 102 pcf

$$\text{Void} = \frac{2.65(62.4) - 102}{2.65(62.4)} \text{ x lOO}$$

$$= 38.3\%$$

$$\text{Volume of voids} = 38.3(3) \text{ x } \frac{27}{100}$$

$$= 31 \text{ ft.}^3$$

Example 2.3

Using the following data, determine the moisture content, absorption, and free moisture in a sample of fine aggregate. If 75 lb of the sample is used in the mix design of concrete, what is the amount of water contributed to the mix by the fine aggregate (FA)?

Initial sample weight = 1.2 lb

Saturated surface dry weight = 1.14 lb

Oven-dry weight = 1.06 lb

Solution

$$\text{Moisture content} = \frac{1.2 - 1.06}{1.06} \times 100$$

$$= 13.2\%$$

$$\text{Absorption} = \frac{1.14 - 1.06}{1.06} \times 100$$

$$= 7.5\%$$

$$\text{Free moisture} = 13.2 - 7.5$$

$$= 5.7\%$$

Amount of water contributed

$$\text{to the mix by FA} = \frac{5.7 \times \_\,].2\_}{100}$$

$$= 4.28 \text{ lb}$$

2.3 TESTING

A number of laboratory tests are described in this section. Following is a list of aggregate properties and the corresponding test numbers.

PROPERTY	TEST NO.
Specific gravity of coarse aggregate	AGG-1
Specific gravity of fine aggregate	AGG-2
Absorption of coarse aggregate	AGG-1
Absorption of fine aggregate	AGG-2
Bulk density of aggregates	AGG-3
Voids in aggregates	AGG-3
Moisture content of aggregates	AGG-4
Sampling of aggregates	AGG-5
Gradation of aggregates	AGG-6, AGG-7

Test AGG-1: Specific Gravity and Absorption of Coarse Aggregate

Purpose: To determine the specific gravity (bulk and apparent) and absorption capacity of coarse aggregate (AGG-5).

Related standard: ASTM C127.

Definitions: *Specific gravity* is the ratio of weight in air of a unit volume of a material to the weight of equal volume of water.

Bulk specific gravity is the ratio of the weight in air of a unit volume of aggregate (including the permeable and impermeable voids in the particles, but not including the voids between the particles) to the weight of an equal volume of water.

Apparent specific gravity is the ratio of the weight in air of a unit volume of the impermeable portion of aggregate to the weight of an equal volume of water.

Absorption is the increase in weight of aggregate due to water in the pores, but not including water adhering to the outside surface of the particles, expressed as a percentage of the dry weight.

Equipment: Balance, wire basket (of 3.35 mm or finer wire mesh), water tank, oven

Sample: A minimum of 4000 gm (8.8 lb) test sample for aggregate of maximum nominal size 1 in. (25 mm). The sample should not have particles of size less than 0.187 in. (4.75 mm).

Procedure:

1. Weigh the test sample: *A* (g).
2. Immerse the aggregate in water at room temperature for a period of 24 ± 4 h.
3. Remove the sample from the water. Roll it in a large absorbent cloth until all visible films of water are removed. The sample is now in saturated surface dry (SSD) condition.
4. Weigh the sample and obtain its saturated surface dry weight: *B* (g).
5. Place the SSD sample in the wire basket and determine its weight in water: C (g). Note that the wire basket should be immersed to a depth sufficient to cover it and the test sample during weighing.
6. Remove the sample from the wire basket.
7. Dry the sample to constant weight at a temperature of 110 ± 5° C (approximately 24 h.), and weigh: *D* (g).
8. Calculate specific gravity and absorption.

$$\text{Bulk specific gravity, dry} = \frac{A}{B-C}$$

$$\text{Bulk specific gravity, SSD} = \frac{B}{B-C}$$

$$\text{Apparent specific gravity} = \frac{D}{D-C}$$

$$\text{Absorption} = \frac{B-D}{D} \times 100$$

Report: Report the specific gravity and absorption values for ¾-in. gravel, ¾-in. crushed stone, and ½-in. crushed stone in tabu1ar form.

Test AGG-2: Specific Gravity and Absorption of Fine Aggregate

Purpose: To determine the bulk specific gravity, apparent specific gravity, and absorption of fine aggregate (AGG-5).

Related standard: ASTM C128.

Definitions: Refer to Test AGG-1.

Equipment: Balance, pycnometer (or a volumetric flask of 500 cm^3 capacity or a fruit jar fitted with a pycnometer top), oven.

Sample: About 500 g of fine aggregate sample.

Procedure:

1. Weigh the test sample: A (g).
2. Cover the test sample with water, either by immersion or by the addition of at least 6% moisture to the sample, and permit to stand for 24 ± 4 h.
3. Decant excess water with care to avoid Joss of fines. Spread the sample on a flat nonabsorbent surface exposed to a gently moving current of warm air, and stir frequently to secure homogeneous drying. Continue until the sample approaches a free-flowing condition. When the specimen has reached a surface dry condition, it is called saturated surface dry (SSD).
4. Weigh the SSD sample: B (g).
5. Fill the pycnometer with water to the top, and weigh: C (g).
6. Remove part of the water and introduce the SSD sample into the pycnometer.
7. Fill with additional water to approximately 90% of its capacity.
8. Roll, invert, and agitate the pycnometer to eliminate All air bubbles.
9. Bring the water level in the pycnometer to its calibrated capacity.
10. Determine the total weight of the pycnometer, specimen, and water: D (g).
11. Remove the sample from the pycnometer, dry to constant weight at a temperature of 110 ± 5° C, cool, and weigh: E (g).
12. Calculate the specific gravity and absorption.

$$\text{Bulk specific gravity, dry} = \frac{A}{C+B-D}$$

$$\text{Bulk specific gravity, SSD} = \frac{B}{C+B-D}$$

$$\text{Apparent specific gravity} = \frac{E}{C+E-D}$$

$$\text{Absorption} = \frac{B-E}{E} \times 100$$

Report: Report the specific gravity values for all the types of fine aggregate.

Test AGG-3: Unit Weight and Voids in Aggregate

Purpose: To determine unit weights of and voids in a sample of coarse, fine, or mixed aggregates (AGG-5).

Related standards: ASTM C29, C127, Cl28.

Definitions:

- *Air void* is a space filled with air.
- *Unit weight* or *bulk density* is the weight in air of a unit volume of a permeable material (including both permeable and impermeable voids).

Equipment: Balance, ½-in.-diameter tamping rod (24 in. long), cylindrical metal measure (minimum capacity of ½ ft^3 for coarse aggregate of size not larger than *I½* in. and of 1/io ft^3 for fine aggregate).

Sample: Aggregate dried to constant weight, preferably in an oven at 110 ± 5° C.

Procedure:

1. Find the empty weight of the metal measure.
2. Fill the measure with the dry sample one-third full.
3. Rod the layer of aggregate with 25 strokes. (Do not allow the rod strike the bottom of the measure.)
4. Fill the measure two-thirds full, level, and rod as in step 3.
5. Fill the measure overflowing and rod as in step 3.
6. Level the surface of the aggregate with a finger and tamping rod such that any slight projection of the larger pieces of the coarse aggregate approximately balance the larger voids in the surface below the top of the measure.
7. Weigh the measure with the aggregate and find the net weight of the aggregate: A.
8. Calculate the unit weight: B.

$$\text{Unit weight or bulk density, } B = (AIV) \text{ lb/ft}^3 \text{ or kg/m}^3$$

where Vis the volume of the measure.

9. Calculate the void content or percent void.

$$\text{Void}(\%) = \frac{S\ X\ W - B}{S\ X\ W} \text{ x } 100$$

where S is the bulk specific gravity (dry basis) from Test AGG- or AGG-2 and Wis the unit weight of water (62.4 lb/ft^3 or 999 kg/m^3).

Report: Calculate unit weight and void for gravel, ¾-in crushed stone, ½-in. crushed stone, and sand. Comment on the results.

Test AGG-4: Total Moisture Content and Surface Moisture Content of Aggregate

Purpose: To determine the percentages of total moisture and surface moisture in a sample of aggregate (AGG-5).

Related standards: ASTM C566, Cl27, C128.

Definitions:

- *Moisture content* (total) *is* the weight of water in the particles expressed as a percentage of dry weight of the particles.
- *Absorption* is the increase in weight of aggregate due to water in the pores, but not including water adhering to the outside surface of the particles, c:xpressed as a percentage of the dry weight.
- *Surface moisture* is equal to the difference between the total moisture content and the absorption.

Equipment: Balance, oven.

Sample: A minimum of 4000 g of coarse aggregate (l in. maximum size) or 500 g of fine aggregate.

Procedure:

1. Weigh the sample: A (g).
2. Dry the sample to constant weight in an oven at 110 ± 5° C for approximately 24 h and cool.
3. Weigh the dried sample: B (g).
4. Calculate the moisture content.

$$\text{Total moisture content} = \frac{A - B}{B} \text{ x } 100$$

Surface moisture content = total moisture content - absorption 1

Note: Absorption is calculated in Test AGG-J or AGG-2.

Test AGG-5: Reducing Field Sample of Aggregate to Test Sample

Purpose: To obtain laboratory samples of aggregates from stockpiles.

Related standards: ASTM C702, D75.

Equipment: Shovel, scoop, broom.

Procedure:

1. Obtain a sample of aggregate [about 110 lb (50 kg)] from three places in the stockpile: from the top third, at the midpoint, and at the bottom third of the volume of the pile.
2. Place the field sample on a hard, clean level surface.
3. Mix the material thoroughly by turning the entire sample three times.
4. Shovel the entire sample into a conical pile.
5. Carefully flatten the conical pile to a uniform thickness and diameter by pressing down the apex with a shovel. (The diameter should be approximately four to eight times the thickness.)
6. Divide the flattened mass into four equal quarters with a shovel.
7. Remove two diagonally opposite quarters. Brush the cleared spaces clean.
8. Mix and quarter the remaining material until the sample is reduced to the desired size.

Test AGG-6: Sieve Analysis of Coarse Aggregate

Purpose: To determine particle-size distribution and fineness modulus of coarse aggregate (CA) by sieving.

Related standard: ASTM C136.

Definition:

- *Fineness modulus* is the sum of the total percentages of material in the sample that is coarser than (cumulative percentages retained) each of the following sieves and divided by 100: No. 8, No. 4, ¾in.,¾in., 1½in., and larger, increasing in the ratio 2:1.

Equipment: Balance, sieves, mechanical shaker, oven.

Sample: Dry coarse aggregate of weight equal to

Weight of sample [lb(kg)]		Maximum size of CA [in.(mm)]	
33	(15)	1½	(37.5)
22	(10)		(25)
11	(5)	¼	(19)

Use the same weight (same as that for ¾ in.) when the maximum size is less than ¾ in. (19 mm).

Procedure:

1. Dry the sample to constant weight at a temperature of 110° C (230° F) if the sample is Lightweight or is suspected of containing appreciable amounts of material finer than a No. 4 sieve.
2. Weigh the dry sample accurately.
3. Weigh each empty sieve and the pan.
4. Nest the suitable sieves in order of decreasing size of opening from top to bottom. Place the pan at the bottom of the set. *Sieves:* No. 8, No. 4, :½ in., ½ in., ¾ in., 1 in., 1½ in. (and higher if needed).
5. Place the sample on the top sieve.
6. Place the lid, and agitate the sieves in the mechanical shaker for about 10 min.
7. Weigh the sieves with the material retained.
8. Determine the weight retained in each sieve. The total weight of the material after sieving should check closely with the original weight of the sample. If the amount differs by more than 0.3% (based on the original weight), the results should not be used.
9. Calculate the percentage coarser than and the percentage passing (refer to Example 2.1).
10. Draw the particle distribution curve and calculate the fineness modulus and the average size of the sample.

Report: Show the particle-size distribution. Report the fineness modulus and average sample size.

Test AGG-7: Sieve Analysis of Fine Aggregate

Purpose: To determine particle-size distribution and fineness modulus of fine aggregate by sieving.

Related standard: ASTM C136.

Equipment: Balance, sieves, mechanical shaker, oven.

Sample: 500 g of dry fine aggregate.

Procedure:

1. Dry the sample to constant weight at a temperature of about 110° C (230° F).
2. Weigh the dry sample, the empty sieves, and the pan.

3. Nest the following sieves in order of decreasing size of opening from top to bottom and place the pan at the bottom of the set. *Sieves:* No. 100, No. 50, No. 30, No. 16, No. 8, and No. 4.
4. Place the sample on the top sieve.
5. Place the lid and agitate the sieves in the mechanical shaker for about 10 min.
6. Weigh the sieves with the material retained. Determine the weight retained in each sieve. The total weight of the material after sieving should check closely with the original weight of the sample. If the amount differs by more than 0.3% (based on the original weight), the results should not be used.
7. Calculate the percentages coarser than and the percentages passing (as in Test AGG-6).
8. Draw the gradation chart. Calculate the fineness modulus and the average size of the sample.

Report: Draw the particle-size distribution. Report the average size of the sample and the fineness modulus.

CHAPTER 3

Concrete and Other Cementitious Materials

Concrete, as it is known today, is a construction material, the properties of which may be predetermined by design, selection of constituent materials, and quality control. The constituent materials are:

- Cement
- Aggregates
- Water
- Admixtures

These ingredients are mixed together and molded into the desired size and shape when the mixture is still wet. Within a few hours of mixing, the cement and water undergo a chemical reaction, referred to as *hydration.* The products of reaction, which continues with time, are hard, strong, and durable. This hard material is called *concrete.*

Cement, also called *hydraulic cement,* is a finely pulverized material that develops its binding property as a result of its reaction with water. The resulting product is stable and water resistant. A type of cement derived from calcination of gypsum or carbonates (such as limestone) is nonhydraulic because the hydration products are not resistant to water. Hydrated lime [$Ca(OH)_2$], which is the product of reaction between quicklime (CaO) and water, is not stable in water and is nonhydraulic. But it can slowly carbonate in air (reaction with CO_2) to form a stable product, limestone ($CaCo_3$). *(Hydrated lime* is the product that results when quicklime is finely crushed, slaked with a minimum amount of water, and then ground to form a fine homogeneous powder. It is white in color and has a specific gravity of 2.08. It is often added to portland cement mortars in varying proportions to increase their plasticity and workability. Further details on properties and uses of hydrated lime are given in Chapter 4.)

The term *portland cement* is used to describe a hydraulic cement produced by pulverizing clinkers consisting essentially of hydraulic calcium silicates. The following paragraph gives a brief history of the manufacture of portland cement.

Joseph Aspdin, a bricklayer of Leeds, England first used the term *portland cement* in 1824 to describe a patented cementitious product formed by heating a mixture of clay and limestone or chalk in a furnace to a temperature sufficiently high to drive off carbon dioxide. The term *portland* was used because the appearance of the mixed concrete resembled natural stones on the Isle of Po1tland, Dorset County, England. He calcined his raw materials only until the carbonic acid was removed entirely. Today the raw materials are heated to incipient fusion. Dav.id Saylor of Allentown, Pennsylvania, who was granted a patent in 1871, is credited with the manufacture of cement in the United States. The *fust* rotary kiln for the manufacture of portland cement was erected in 1886 at Roundout, New York.

In addition to concrete, portland cement is also used to manufacture other cementitious materials, such as mortar, grout, stucco, and shotcrete (Fig. 3.1). *Mortar* is a mixture of sand, cement, hydrated lime, and water. It is used to bond individual bricks or blocks of a masonry wall, and also for plastering. *Grout* is a mixture of cement, sand, and fine gravel to which sufficient water is added so as to be able to pour without

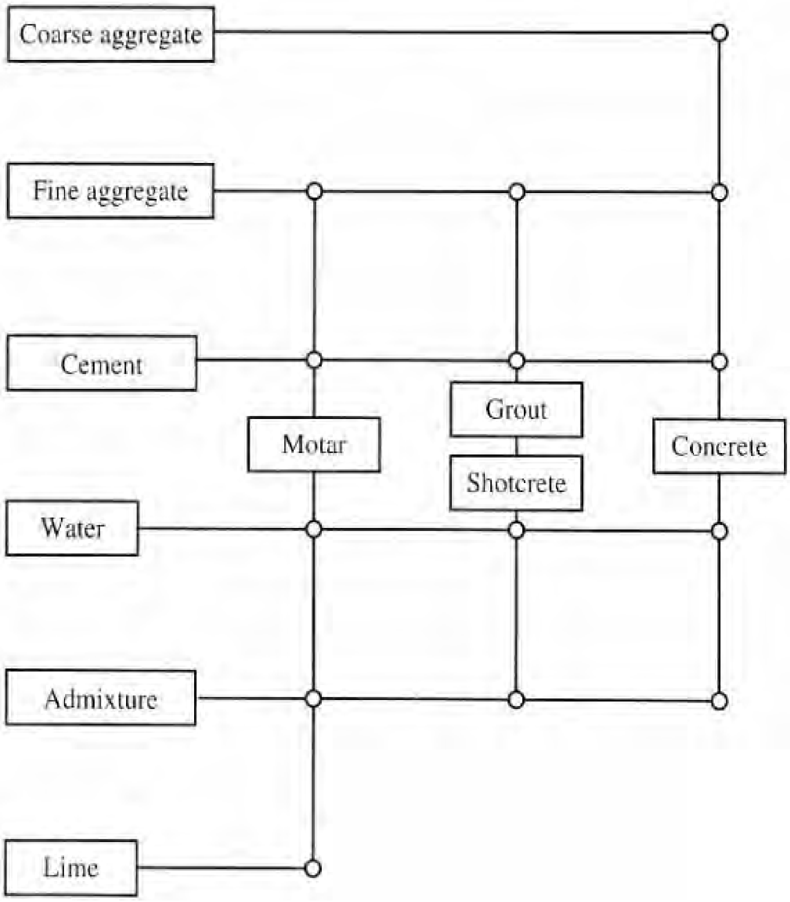


Figure 3.1 Concrete and other cement-based materials.

segregation. (*Segregation* refers to the tendency for the large and fine particles in fresh concrete to become separated, resulting in a porous and honeycomb structure.)

Stucco is a type of plaster made with cement, water, and fine sand with or without hydrated lime. It can be applied (generally in three coats) directly to masonry walls, but ver wood sheathing some type of wire mesh must be used to tie the stucco and sheathing together. It is a durable wall covering that is strong, fire resistant, and fungus resistant. *Shotcrete* (also called *gunite* or *spray concrete)* refers to pneumatically placed concrete in which a dry mixture of cement and sand is blown through hoses, and water is injected at the nozzle. The maximum size of aggregate for shotcrete is generally ¾ in. This material or technique is employed for the repair of damaged structures and in the construction of domes, shells, tunnel linings, culverts, and swimming pools. Shotcrete is also used to repair and rehabilitate structures damaged by freeze-thaw action, aggressive chemicals, and fire, such as bridges, culverts, sewers, and dams.

3.1 USES OF CONCRETE

Concrete is one of the most common construction materials and is used in a wide variety of applications, ranging from piles to multistory buildings and from railroad ties to dams. It is also used in foundations, pavements, walkways, storage tanks, and many other structures. In fact, it is hard to find structural applications where concrete is not used in one form or another. It is one of the most economical materials of construction and is very versatile in nature and application.

Important properties of concrete are:

- Strength
- Durability (weather resistance)
- Wear resistance
- Impermeability
- Abrasion resistance
- Resistance to environmental attacks (from sea salts, sulfates in the soil, etc.)

Not all of these properties are important for every application, but most are. For example, in a liquid-retaining structure such as a storage tank or dam, the primary requirements are impermeability, resistance to chemical attacks from liquids, and weather resistance. In nonstructural applications, such as building facades and sign walls, concrete may also be required to possess adequate thermal resistance, light weight, and pleasing appearance.

Unlike wood and steel, which deteriorate through action with water, concrete possesses excellent resistance to water. This property is used in building concrete clams, aqueducts, pipes, canals, storage tanks, and foundations. Freshly made concrete is plastic in consistency and can easily be molded into any shape and size, and is thus used for shells, folded plates, circular pipes, and arches. The materials for the manufacture of concrete are easily available and are inexpensive. Large amounts of industrial waste products can also be recycled and used as ingredients in concrete preparation.

Concrete derives its strength and properties from those of aggregates, the type and quality of cement, and the mix proportions. It should be noted that the aggregates themselves are not transformed in the concrete mixture, and that the reaction between cement and water produces compounds that harden with time and bond the individual aggregate particles. Thus, to understand the properties of concrete, it is important to understand the composition of cement and the chemical process that follows when cement comes in contact with water.

3.2 CEMENT AND ITS TYPES

Portland cement was first manufactured in the United States during the later part of the nineteenth century. It is produced at present by heating a carefully controlled mixture of limestone and clay (with and without secondary raw materials such as bauxite and iron ore) at a very high temperature, and by grinding the resulting product into powder. Most of the ingredients for the manufacture of cement are found in nature. Limestone, shale, slate, clay, chalk, marl (a natural soil deposit found in lake bottoms and swamps, consisting of clay and calcium carbonate, used especially to fertilize soils deficient in lime), silica sand, and iron ore are plentiful throughout the world. Each manufacturing plant may use a different combination of raw materials, although limestone and clay are the most common.

The three primary constituents of raw materials in the manufacture of cement are:

- Lime
- Silica
- Alumina

Lime is obtained from limestone and chalk, and silica and alumina are obtained from clays, shales, and bauxite. In addition to these ingredients, most cements contain small amounts of iron oxide (from iron ore or clay), magnesia, sulfur trioxide, alkalies, and carbon dioxide. But lime (CaO) and silica (SiO_2) make up about 60 and 20% of the ingredients in cement, respectively. Iron oxide and aluminum oxide (alumina) account for about 10% of the raw materials.

Portland cement is manufactured by one of two basic processes: *wet* and *dry*. In both, the raw materials (limestone, clay, and others) are homogenized by crushing, grinding, and blending. Approximately 80% of the raw materials pass a No. 200 sieve. In the wet process, the mix, in the form of a slurry containing about 30 to 40% water is heated in horizontal revolving kilns to about 2750° F (1510° C), at which temperature oxides of calcium and silica are combined to form cement clinkers. The rotation of the kiln plus its shape allow the mix to flow down the kiln and gradually increase in temperature. In the dry process the mix is fed into the kiln and burned in a dry state. The dry process provides a considerable savings in fuel consumption and water usage but is dustier.

In the kiln, initially, water from the raw materials is driven off and limestone is decomposed into CaO and carbon dioxide. These products then undergo a solid-state chemical reaction in the burning-zone portion of the kiln, which produces calcium silicate and other compounds. These products, which are greenish black in color, are in the form of pellets, called *clinkers*.

The cement clinkers are hard, irregular ball-shaped particles (about¾ in. or 18 mm in diameter), and as mentioned above, are generally black or greenish black in color. These are cooled (to about 150° F) and stored in clinker silos. When needed, the clinkers are mixed with about 2% gypsum (to retard the setting time of the resulting cement) and then ground to a fine powder (particles less than 75 µm in diameter) in ball mills or a roller press. The cement is then stored in storage bins and bagged for shipment. In the United States a bag of cement weighs 94 lb (42.6 kg) and has a volume of about l ft^3 (0.028 m^3) when packed. These bags should be stored in a dry place on pallets, preferably covered with tarpaulins or similar waterproof covering. Cement that comes in contact with moisture forms lumps and sets more slowly than does cement that is kept dry.

About 75% of cement is composed of calcium silicates; compounds of aluminum (Al_20_3), iron (Fe_20_3), and gypsum ($CaSo_4$) make up the balance. The four major compounds of cement are:

- Tricalcium silicate (C_3S)
- Dicalcium silicate (C_2S)
- Tricalcium aluminate (C_3A)
- Tetra calcium aluminum ferrite (C_4AF)

These compounds, their chemical compositions, and abbreviated symbols are shown in Table 3.1. In the cement chemistry it is an accepted practice to use simple nomenclature for the compounds of cement. In addition to these four main ingredients, minute quantities of other compounds are also found in cement but are not listed in Table 3.1. Depending on the relative quantities of these compounds, the properties of hardened cement vary. When any of these compounds come in contact with water, hydrates of various compounds are produced which give hardness and strength to the mix. This process, called *hydration,* is explained in Section 3.3. Portland cement is manufactured in eight different types through modifications in the relative amounts of the main ingredients and the fineness of the particles (Table 3.2): type I, type IA, type II, type HA, type TU, type IHA, type IV, and type V.

Type I cement (standard portland cement) is a general-purpose cement and the most commonly used portland cement. It is employed when special properties of any other types are not required. Type *IA* is the air-entraining type I cement, which is obtained by the addition of an interground air-entrainment admixture.

Type II cement (modified port/and cement) is a general-purpose cement used when moderate sulfate resistance or moderate heat of hydration is desired. Type TIA is the air-entraining type II cement, similar to type lA cement. Type II (and type IIA) cement have better resistance to the action of sulfates than does normal type l cement and is used where sulfate concentration in groundwater is higher than normal but is not severe. The heat of hydration generated by this cement is at a slower rate than type I cement, and thus can be used in mass concrete work. The lower heat of hydration is also advantageous when placing concrete in hot weather. This type of cement is used, *for* example, in highway pavements, foundations, reservoir lining, high-rise buildings, piers, and massive structures.

TABLE 3.1 PRINCIPAL COMPOUNDS OF CEMENT

Compound	Chemical formula	Industry Code (abbreviation)	Percent Amount (range)	Rate of reaction With water
Tricaldum silicate	$3Ca0 \cdot Si0_2$	C_3S	35-65	Medium
Dicalcium silicate	$2Ca0 \cdot Si0_2$	C_2S	15-40	Slow
Tricalcium aluminate	$3Ca0 \cdot A1_20_3$	C_3A	0-15	Fast
Tetra calcium alurninofenite	$4Ca0 \cdot Al_20_3 \cdot Fe_20_3$	C_4AF	20	Medium

TABLE 3.2 CEMENT TYPES AND USES

Cement types	Standard chemical requirements				Uses
	C_3S (max.)	C_2S (min..)	C_3A (max.)	C_4AF $+2C_3A$ (max.)	
J and IA					General use; when special properties are not required
II and IIA			8		General use; has moderate sulfate resistance and heat of hydration
Ill and II1A			15		When high early strength is required
IV	35	40	7		When low heat of hydration is required
V			5	25	When high sulfate resistance is required

Type III cement (high early strength cement) is for use when high early strength is desired. Type IHA is type III cement with an air-entraining admixture. Types I and III typically contain more C_3A than do types II and V cements. Type III cement is made use of when the formwork is to be removed as early as possible and the structure is to be brought into service quickly. It is also used in cold weather operation to decrease the time needed to protect concrete from freezing. Concretes made with this cement set and harden rapidly. The compressive strength of concrete made with type III cement in 24 hours is about equal to that of concrete made with type I cement after 3 days.

Type IV cement (low-heat cement) is for use when low heat of hydration is desired, and *type V cement (sulfate-resistant cement)* is required when sulfate-resistant concrete is needed. The compounds C_3S and C_3A produce high heat of hydration. Low-heat cement is manufactured by limiting the amounts of C_3A and C_3S to 7 and 35%, respectively. *This* cement is suitable for very large structures (e.g., concrete dams), where the use of ordinary cement would result in a large temperature gradient within the cross section. The rate of hydration of this type of cement is slower than that of type I cement, although the final strengths (long term) of the two are nearly the same. Type IV cement is no longer manufactured in the United States since its use has been eliminated.

Type V cement is for use where sulfate concentration is very high and in seawater. Sulfates (sodium, calcium, and magnesium) are often found in soils and water. They attack concrete by reacting with $Ca(OH)_2$ in the cement to produce gypsum (calcium sulfate) and other products. Calcium sulfate reacts primarily with C_3A to produce mainly expansive tricalcium sufflaminate and calcium hydroxide. [Note that $Ca(OH)_2$ is a compound that is produced during hydration.] These products cause volume expansion in concrete.

Cements containing low amounts of C_3A (generally less than 3%) have higher resistance to sulfate attack. Thus type V cement, which has a maximum limit of 3% C_3A, is best suited for construction requiring very high sulfate resistance. But it should be noted that factors other than the amount of tricalcium aluminate (such as the ratio between tricalcium silicate and dicalcium silicate) are also found to affect sulfate resistance. Use of type V cement, however, may increase the corrosion danger in reinforced concrete construction. This should be verified through tests.

Type V cement is commonly chosen for concrete construction in seawater and inland lake water, for sewage disposal sites, and for other, special uses. This type of cement is somewhat resistant to the destructive action of organic acids.

The sulfate resistance of concrete can also be improved by adding pozzolans such as fly ash with ordinary cement. The addition of pozzolans to cement will remove the excess calcium hydroxide from the hydrated cement paste and thus provide a more stable environment against deterioration.

Air-entraining cement in any type can be used to obtain air-entrained concrete. However, it is general practice to add air-entraining admixtures (to normal cements) during concrete manufacture since the quantity of the admixture can be varied to satisfy the design requirements. Additional particulars on air-entrained concrete and pozzolans are furnished in Section 3.9.

3.3 SETTING AND HYDRATION

Dry cement does not possess the cementing or binding property. Chemical reaction between compounds of cement and water yields products that achieve the binding property after hardening. This process or reaction between cement and water is called *hydration.*

3.3.1 Setting

When cement is mixed with sufficient water, the resulting paste loses its plasticity and slowly forms into a hard rock. In the beginning the paste loses its fluidity and within a few hours noticeable stiffening results. This is called the *initial set* and is measured by the ability of the paste to withstand a certain arbitrary pressure. Further buildup of hydration products is followed by commencement of .the hardening process, responseble for the strength of concrete, which is known as the *final set*. The time from the addition of water to the initial and final set are known as the *initial setting time* and the *final setting time*.

For type I cement the initial and final setting times are about 2½ and 3½ hours, respectively. These values are affected by the amount of water in the mix, the composition of cement, the temperature, and the fineness of cement. (Note that *fineness* refers to the size of cement particles. The finer the cement, the faster is the rate of hydration and the strength development.) Mixes with higher water content take a longer time to set. The higher the ambient temperature, the more rapid is the setting.

In cement paste and concrete, setting occurs within a few hours, but hardening, which is the development of strength over an extended period of time, is not completed for months. The process of hardening is explained in the following paragraphs. Setting -is also a measure of the rate of release of heat of hydration. The compound gypsum, which is added to clinker in the manufacture of cement, retards setting, and the use of hot water (for mixing) accelerates setting.

3.3.2 Hydration

Portland cement is a mixture of several compounds, all of which can hydrate with water. Hydration is the key for the strength development in concrete. But all compounds do not hydrate at the same rate, and as a consequence, the rate of strength development is a function of time and temperature. The aluminate (C_3A) is the most reactive compound in cement and hydrates at a much faster rate than do the silicates. The stiffening characteristics and setting times are due largely to the hydration products involving aluminates. In fact, the addition of gypsum to clinkers is to slow down the hydration of tricalcium aluminate. The silicates, however, play a dominant role in the hardening process, which is responsible for the strength development.

Tricalcium silicate (C_3S) hardens rapidly and is largely responsible for the early strength development. Dicalcium silicate (C_2S) hardens slowly and is responsible for strength increase beyond 1 week. Tricalcium aluminate also contributes to the early strength development of concrete. The rate of hydration of any cement depends on the relative proportions of silicates and aluminates, the fineness of cement, and the ambient temperature and humidity.

The calcium silicates (tricalcium and dicalcium), which constitute about 75% of the cement, react with water to form two new compounds: calcium hydroxide and calcium silicate hydrate. The physical properties of the paste and the mechanical properties of hardened concrete depend primarily on calcium silicate hydrate. This product occupies about 50 to 60% of the volume of solids in a completely hydrated paste.

It is estimated that on complete hydration, I cm^3 of cement occupies a volume of 2 cm^3, which means that 1 cm^3 of dry cement produces hydration products that occupy 2 cm^3 of volume. **1n** other words, **1** g or lb of cement requires about 0.3 lb or g of water for complete hydration to take place. (Note that the specific gravity of cement is 3.15.)

Thus hydration can also be conceptualized as a process during which the space previously occupied by cement and water is being replaced more and more by the products of reaction between the two. The space not used up by cement or hydration products makes up for the voids or pores that are filled with water and air. They (the pores) possess no strength, and the strength of paste is that in its solid part.

3.3.3 Heat of Hydration

Hydration is always accompanied by release of heat; in other words, the hydration reactions of portland cement compounds are *exothermic*. The amount of heat *(heat of hydration)* generated depends on the chemical composition of the cement, the fineness of cement, and the ambient temperature. A temperature rise as high as 45° F (23°C) has been observed in the past in concrete dams. Tricalcium aluminate liberates the most heat; dicalcium silicate liberates the least. The former causes *flash set* when mixed with water, accompanied by the release of considerable heat. A small amount of gypsum added to clinkers is meant to reduce the flash set. Tricalcium silicate releases twice as much heat as does dicalcium silicate. Type IV cement has low levels of C_3A and C_3S and thus generates less heat of hydration.

In massive structures the heat evolved is dissipated so slowly that the temperature of the structure shows a marked increase followed by thermal expansion. Eventually, the interior cools and contracts, which might induce tensile stresses in the interior of the mass. Without any measures to control the heat of hydration, the concrete is bound to crack. The use of low-heat cement and pozzolans will help lower the heat. But in cold weather concreting this heat of hydration is beneficial, helping to maintain continuous hydration. (Note that the rate of hydration decreases with decrease in ambient temperature.)

3.4 PROPERTIES OF CONCRETE

Concrete is a mixture of cement, aggregates, and water (Fig. 3.2). It can also be looked upon as a mixture of aggregates bound together using cement paste, comprised of portland cement and water. The aggregates make up about 60 to 75% by volume of concrete and the paste constitutes about 25 to 40%. Of the cement paste, the volume of cement occupies about 25 to 45%, and water makes up the balance (Fig. 3.3). In addition to these ingredients, fresh concrete also contains air, its volume ranging from 2 to 8% of the volume of concrete.

As we discussed in Chapter 2, aggregates are divided into two types: fine (sand) and coarse (gravel). *Fine aggregate*, particles of size equal to or less than 4.75 mm (or No. 4 sieve), make for about 30 to 45% of the total volume of aggregate. *Coarse aggregate* is made up of particles that are predominantly retained on a No. 4 sieve. Both fine and coarse aggregates consist of particles of various sizes, large to small, so as to produce a mixture of minimum void space. Each particle of coarse and fine aggregates, in concrete, is coated with the cement paste, which when hydrated provides the necessary bond. The strength of the concrete depends on the strength of the aggregate particles and the strength of the paste. Fresh concrete does not possess any strength,

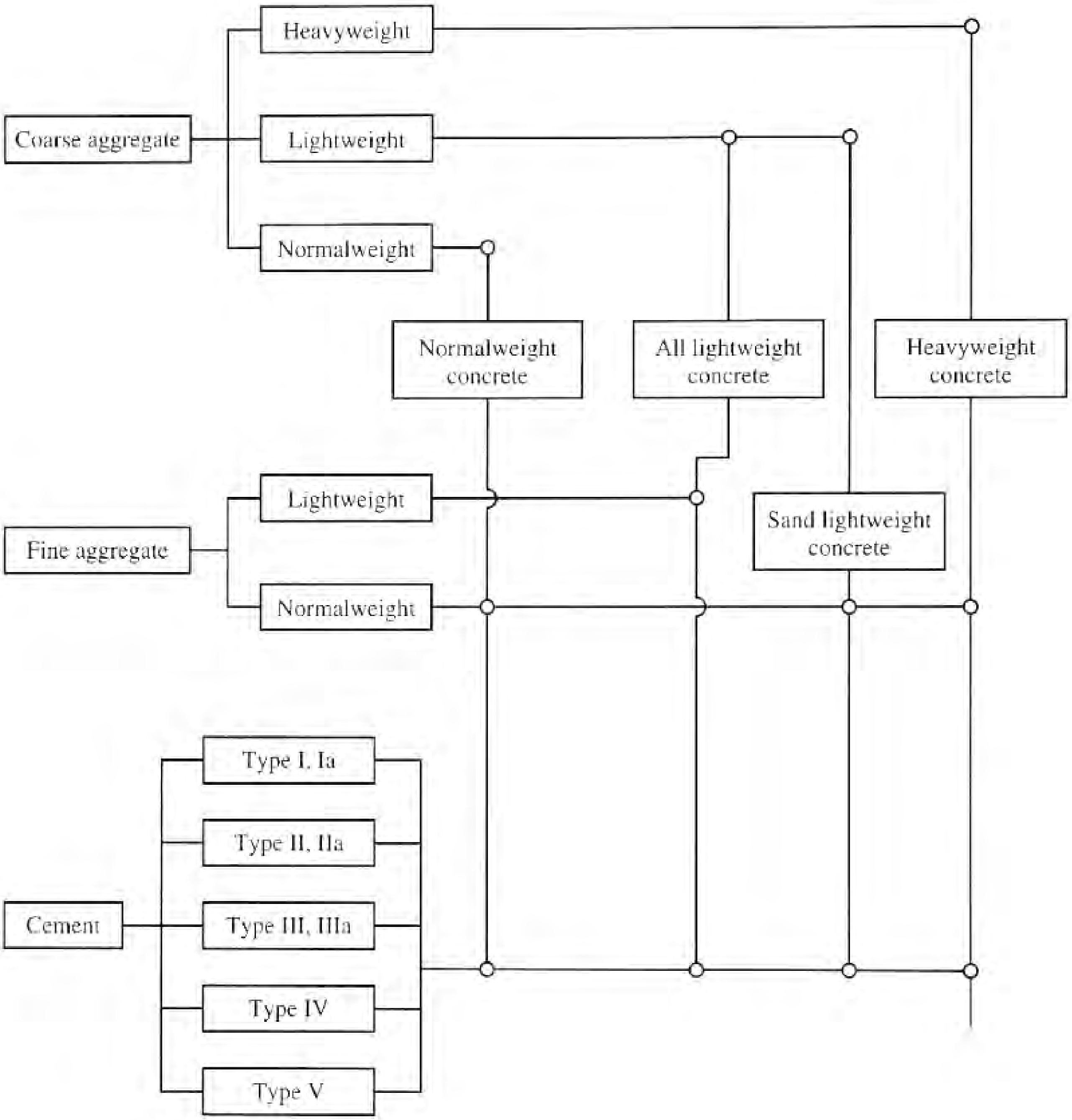
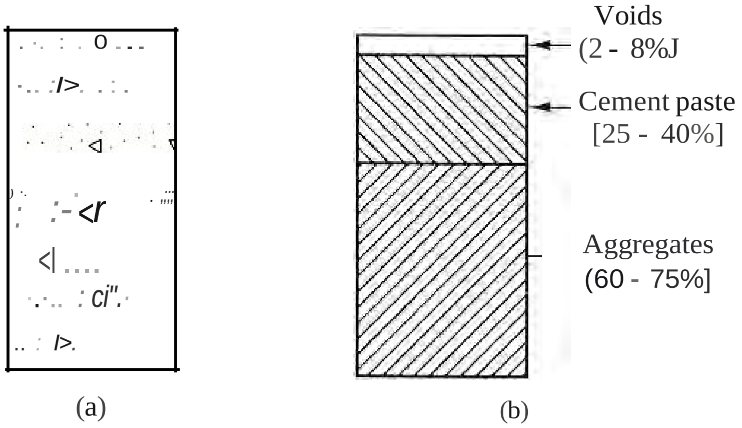


Figure 3.2 Types of concrete.



(a)

(b)

Figure 3.3 (a) Concrete sample; (b) volumetric proportions of constituents.

even though about 75% of its volume is made up of aggregate particles of substantial compressive strength. As the hydration proceeds, the products that result provide increasing strength to the paste, and the concrete is able to carry the applied loads.

It is important to study a number of properties of concrete at both the mixing and solid stages. During the mixing stage, the fresh concrete is plastic and fluid and is capable of being transported, placed, compacted, and molded into any shape. With sufficient hydration, concrete becomes a hard and brittle mass capable of exhibiting structural properties such as adequate compressive strength and stiffness. Unsatisfactory performance during the mixing stage is nearly always an indication of inadequate structural properties in the hardened concrete. Good concrete is concrete that has acceptable qualities in the mixing stage as well as in the solid stage. The properties of fresh and hardened concrete are discussed in the following sections.

3.5 PROPERTIES OF FRESH CONCRETE

Fresh concrete should be such that it can be transported, placed, compacted, and finished without harmful segregation. A proper mix should maintain its uniformity inside the forms and should not bleed excessively. *Bleeding* is the movement and appearance of water at the surface of freshly placed concrete. It is the result of settlement of heavier particles and can be looked upon as a form of segregation. All these aspects of fresh concrete-those associated with several tasks from selection of materials to finishing-are collectively called the workability. Thus *workability* can be defined as the ease with which a fresh concrete mix can be handled from the mixer to the final structure. At present there does not exist a procedure to measure the workability quantitatively. But a nonworkable mixture can easily be identified from the inability to satisfy one or more of the concreting tasks: mixing, transporting, compacting, and finishing.

The three primary characteristics of workability are:

- Consistency
- Mobility
- Compatibility

In addition, for some structures, such as floor slabs, finishability is also a measure of workability.

3.5.1 Consistency

Consistency is a measure of concrete wetness or fluidity, which depends on the mix proportions and properties of the ingredients. It is generally measured with a *slump test* (ASTM C143). The test is also used to measure the characteristics of workability, although it only measures (indirectly) the ease with which concrete can be placed, compacted, and finished without harmful segregation. Thus the slump or slump test can only be used to measure changes in workability or for relative comparison of workability between different mixtures.

The slump test was developed by Chapman in the United States in 1913. It consists of a metal slump cone having a bottom diameter of 8 in. (200 mm) and a top diameter of 4 in. (100 mm) (Fig. 3.4). The height of the cone is 12 in. (300 mm). The cone (whose inside surface is dampened) is placed on a smooth, flat, nonabsorbent surface and is filled with fresh concrete while it is held firmly in place by standing on the foot pieces. It is filled to about one-third of its height, which is then tamped 25 times with a ¾-in. (16-mm) (24-in.-long) tamping rod (Fig. 3.5). The process is repeated two more times when the cone is filled, and the top is struck off with the tamping rod (placed horizontally) so that the cone is filled exactly. The mold is then removed by raising it vertically immediately after filling. The concrete will subside, and the number of inches the center of the cone settles or slumps is measured. This is called the *slump*. A very dry mix will have zero slump, whereas a very wet mix collapses completely, producing unreliable values of slump. Note that the sample of concrete for the slump test is taken immediately after the concrete has been discharged from the mixer, and the slump is measured immediately after the cone is removed.

The slump depends on the ingredients, amount of mixing water, and addition of admixtures. The value of slump also changes with temperature and time after mixing (owing to the hydration process and the evaporation of water). The minimum and maximum slumps recommended for various types of work are given in Table 3.3.

Although the slump test is used to compare the fluidity of a mix with the slump recommended for the job, it can be used for the relative comparison of workability of various concretes. The measured slump may be used to estimate the change in water content necessary to maintain uniformity from batch to batch. It may also be used to indicate the changes in the grading or proportioning of aggregates. But slump test (or measured slump) should not be used to judge the quality or strength of concrete.

Another method of measuring consistency is the *ball penetration test* (ASTM C360). In this test the penetration of a metal weight into freshly mixed concrete is used as a means to determine the consistency or workability of concrete. It consists of a cylinder with a hemispherical shaped bottom and handle weighing 30 lb. A frame is used to guide the handle and to serve as a reference for measuring the depth of penetration (Fig. 3.6). The instrument is set on a freshly placed smooth concrete surface, and the ball is set on the concrete surface with the handle vertical. The weight is released,

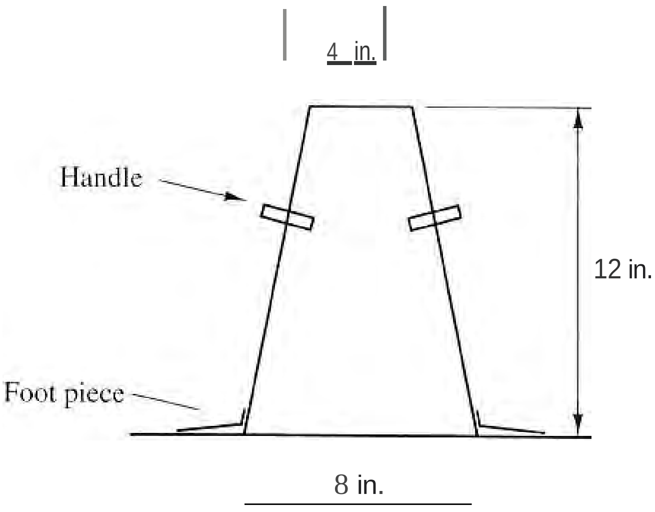
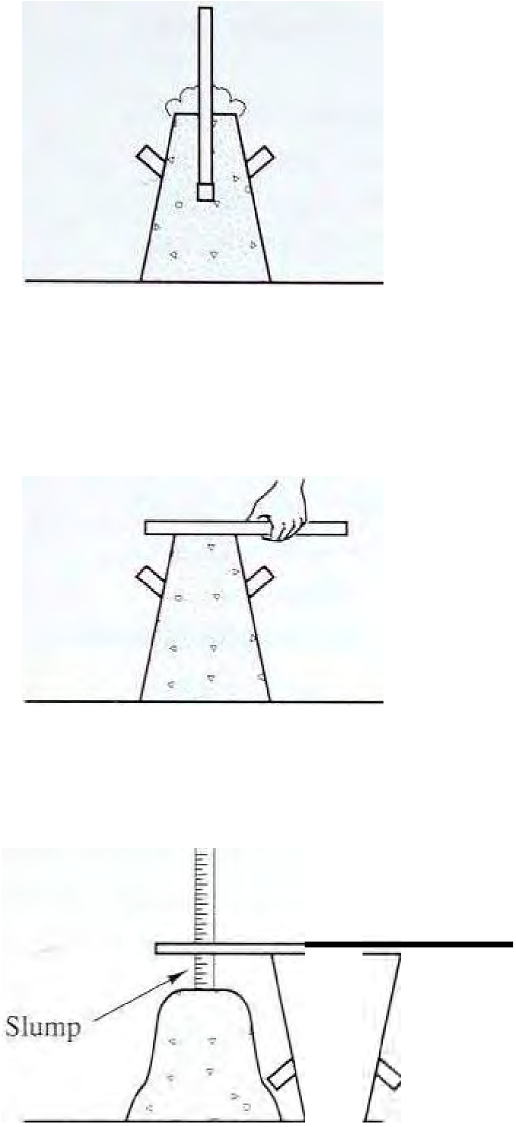


Figure 3.4 Slump cone (mold).



Fill the cone using standard procedure.

Strike off excess.

Raise the mold and measure the displacement of the original center of the specimen.

Figure 3.5 Slump test.

Table: 3.3 RECOMMENDED SLUMPS FOR VARIOUS TYPES OF CONSTRUCTION

Types of construction	Slump (in.) Maximum	Slump (in.) Minimum
Footings. caissons, foundation walls, and substructure walls	3	
Beams, columns, and walls	4	1
Pavements and slabs	3	1
Mass concrete	2	

and the penetration *is* read to the nearest ¼ in. (6.4 mm) after the weight comes to rest. A minimum of three readings are taken from each batch.

3.5.2 Factors Affecting Consistency and Workability

A number of factors influence the consistency and workability of concrete. Workability is relatively insensitive to changes *in* cement content, but is heavily dependent on water content. It decreases with increase in the fineness of cement. Some admixtures, such as

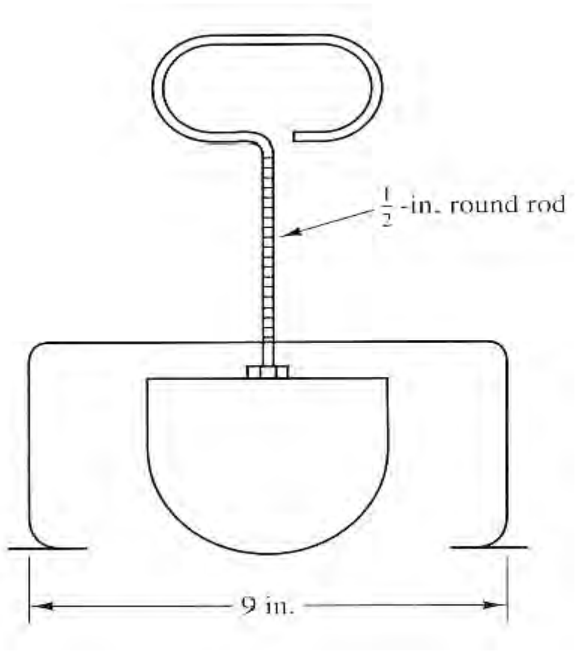


Figure 3.6 Ball penetration apparatus.

the water-reducing admixture (superplasticizers) and the air-entraining admixture, increase the workability of the mix.

Workability decreases with increase in the surface area of aggregates. The surface area is governed by the shape, grading, and maximum size of aggregate. As the maximum size of aggregate is increased and the particles become round, the surface area is decreased and the workability is increased. A coarser gradation increases the workability. As the fineness modulus (measure of the average size of aggregate) increases, the gradation becomes coarser, which increases the workability. An increase in the amount of coarse aggregate improves the workability.

Workability also depends on the rate of hydration and the rate of loss of water through evaporation. With increase in temperature the hydration rate speeds up, thus increasing the rate at which water is used for hydration. In addition, the rate of evapora tion is increased. When the placing of the mix and its compaction are delayed, more water is lost due to evaporation, resulting in a decreased workability.

As indicated earlier, there is no test available to quantify the workability of fresh concrete. However, when a concrete mix cannot be placed, compacted, or finished effectively, it is said to be unworkable. Similarly, when the compacted mix shows a tendency for segregation, it is said to be unworkable.

3.5.3 Segregation

Segregation was defined earlier as the tendency for separation of large and fine particles in a fresh concrete mix. Generally, mixtures that are very wet and deficient in finer particles (finer sand) tend to segregate. Segregation results in a nonhomogeneous mix that affects the strength and durability of hardened concrete. Segregation is one of the causes of pores or pockets and a *honeycombed surface.* Air entrainment decreases the tendency to segregate.

3.5.4 Bleeding and Scaling

A concrete mix that does not possess the proper consistency is unable to hold the mixing water, which is slowly displaced and then rises to the top of the form. This water is either lost due to evaporation or through joints and in the sides of the form. This process of separation of water from the mix is *bleeding.*

Bleeding results in the movement of water and finer particles to the top of the form and produces a nonhomogeneous mix. The water lost through joints in the form and its sides carries with it some cement and results in a weaker concrete. Bleeding is also found to be a cause for the formation of fine cracks below the larger aggregate particles. Overvibration, overtroweling, and lean mixes increase the potential for bleeding. Air entrainment is an effective method of controlling bleeding. Increase in the fineness of cement and/or decrease in the water/cement ratio decreases the bleeding.

Premature finishing may be a cause of excessive bleeding, resulting in the loss of some entrained air and making the concrete vulnerable to scaling. *Scaling* comprises the surface cracks and the removal of surface layer in concrete produced by the pressure generated when the water in concrete pores freezes.

It should be noted that in appropriate amounts, bleeding is beneficial in finishing concrete. The top surfaces of floors, pavements, and roofs have to be finished smooth, which is done by working the concrete before it sets in such a way that the top layer consists of cement paste mixed with finer sand. This layer is then finished smooth with a metal trowel. Bleeding helps in bringing soft materials to the surface of concrete.

3.6 MIXING, PLACING, AND CURING

The purpose of mixing is to ensure that in the fresh concrete, each particle of aggregate will be coated with the cement paste. The mixing can be carried out by hand or machine. The mixing involves weighing out or measuring out all the ingredients for a batch of concrete, and this process is called *batching.* The amounts of materials that are mixed at a time constitute a *batch*, and the size of a batch is usually designated by the number of bags of cement (94 lb or Jft^3 of loose volume) it contains. For example, a six-sack batch refers to a cubic yard of concrete made with six bags or 564 lb (256 kg) of cement.

Hand mixing can be done in a tight wooden or metal box or in a wheelbarrow. First the sand is spread in a uniform thickness and covered by the cement. These materials are given three turns and the mixture is formed into a wide crater. The coarse aggregate is then dumped into this crater. The mixing water is then poured over the gravel, taking great care to ensure that none of the water escapes, and the edges of the pile are gradually turned in to absorb the water. The entire mix is then given four or more complete turns until it is of uniform consistency.

Most concrete is now conveyed to the job site in *mixers*. Concrete is sometimes mixed at the job site in a *stationary mixer* or a *paving mixer*. Concrete that is thoroughly mixed in a stationary mixer, called *ready-mixed concrete* or *ready-mix*, is delivered to the actual construction site either in a truck agitator or a non-agitating truck. A truck agitator is a special truck mixer operating at agitating speeds and is used to transport concrete for all uses, such as pavements, buildings, and foundations. A non agitating truck is used for short hauls.

A truck mixer or *transit mixer* is a special truck used for both mixing and transporting concrete to a job site over short and long hauls. No central mixing plant is needed in this case; a batch plant (or proportioning plant), where exact amounts of ingredients are loaded into the truck, is all that is necessary. The truck carries a mixer and a water tank, from which the driver can add the required amount of water into the mixer at the proper time. Generally, the water is introduced before the truck arrives at the job site or at the batch plant. The mixer is kept revolving slowly in route to prevent segregation of dry particles. The concrete should be conveyed as rapidly and directly as practicable to preserve the quality, and deposited within 90 minutes after adding cement.

A concrete mixer is designated as to its size by the rated capacity of the volume of fresh concrete that can be mixed in a single batch. The rated capacity can be as small as 2 ft^3 (0.06 m^3) and as large as 7 yd^3 (5.35 m^3). A 16-ft^3 mixer is capable of producing a maximum of 16 ft^3 (0.45 m^3) of concrete with a 10% overload capacity per batch.

The ingredients are introduced into the mixer either by hand or with a mechanical skip. When the mixer is equipped with the skip, the dry ingredients are placed in the skip and then dumped into the mixer together while the water runs into the mixing drum from the side opposite that of the skip. The mixing time may vary from about 2 to 5 minutes depending on the volume of concrete. After mixing, the fresh concrete is discharged from the mixer through the discharge chute.

In small *drum mixers* (having revolving drums with fixed blades inside) the ingredients are introduced into the drum by hand. First, part of the mixing water is poured into the drum. Next, part of the gravel is added. Adding gravel to water before the addition of cement prevents cement from sticking to the drum. Then add the measured amount of cement. This should be followed by sand and gravel in proper proportions. The remaining water is then introduced into the drum, and the mixing is continued for 3 minutes. (Note that all ingredients are added when the mixer is running.) Stop the mixing for 2 minutes. Restart the mixer and mix for 2 minutes. Dump the concrete into the wheelbarrow while the mixer is still running.

When proper mixing is employed there is no difference between hand-mixed concrete and machine-mixed concrete. But when the volume of concrete is large, hand mixing does not produce a uniform or homogeneous mixture.

3.6.1 Pumping and Placing

Concrete is conveyed to the construction site in wheelbarrows, carts, belt conveyors, cranes, or chutes. Alternatively, a *concrete pump* can be used to push the concrete to its final position. Pumps must be of adequate capacity and capable of moving concrete without segregation. Concrete pumping is the standard method of placement in high-rise construction. Today's pumps have the capacity for a maximum vertical reach (in single lift) of 1400 ft (420 m) or more and a volume of 170 yd^3 (130 m^3) per hour.

Concrete should be placed as near as possible to its final position. In slab construction, the concrete should first be placed around the perimeter at one end with each batch dumped against previously placed concrete. Concrete should not be deposited in big piles and then moved horizontally to its final position to prevent segregation. In general, concrete should be placed in horizontal layers of uniform thickness (of 6 to 20 in.), and each layer should be completely consolidated before placement of the next layer.

In wall construction, the first batch should be placed at both ends of the section, and the concreting should progress toward the center. The same procedure can be used when placing concrete for beams. When placing concrete in tall forms, bleeding can be prevented by placing it slowly. The free vertical drop of concrete at any point during conveying should not exceed 3 ft.

3.6.2 Tools

A number of tools are required to place, compact, and finish the concrete. Some common tools are shown in Fig. 3.7. Ordinary square-pointed shovels are used for mixing concrete. A wheelbarrow is used to transport concrete from the mixer to the form. A *tamper* consisting of a 4 ft handle on an 8 x 8 x 12 in. (20 x 20 x 30 cm) piece of timber, is used tocompact concrete for sidewalks and pavements. A metal tamper can also be used.

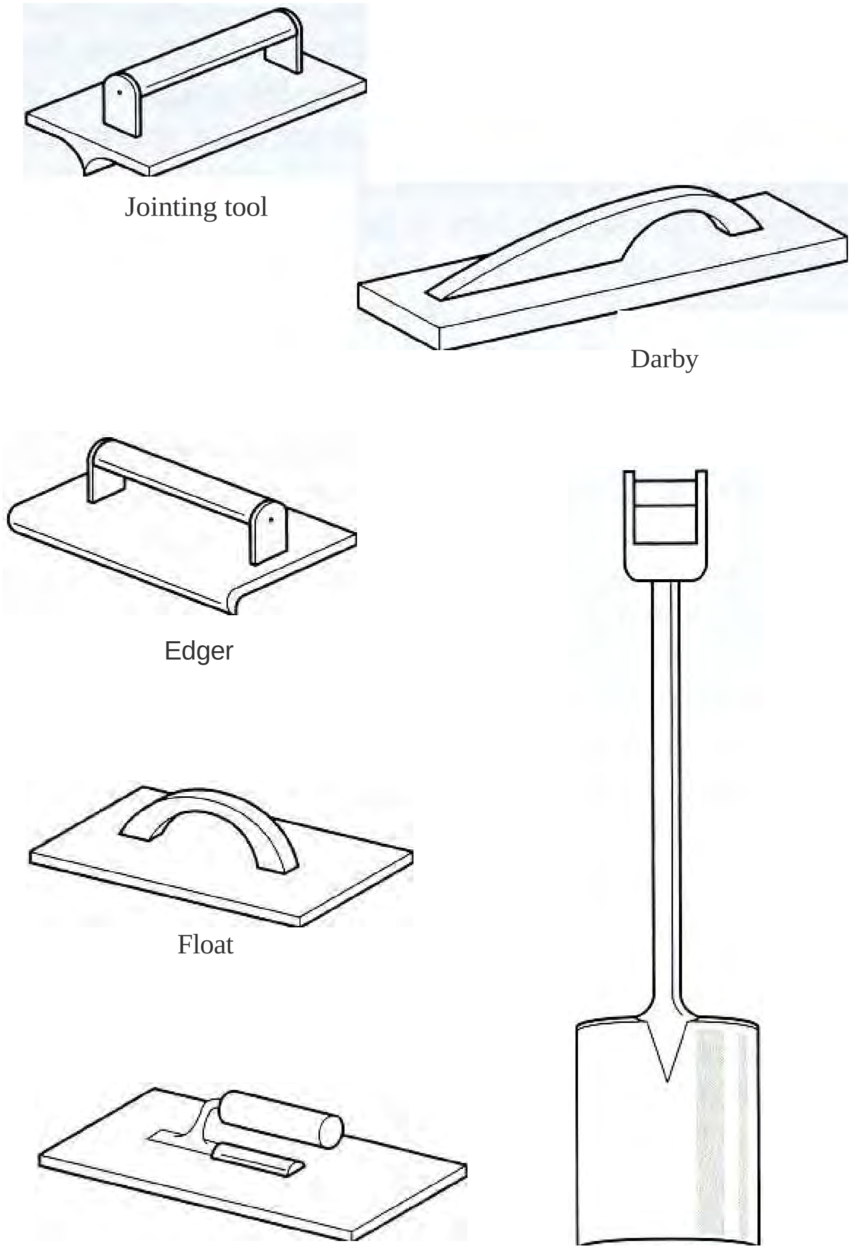
A *strikeboard,* usually of 2 x 4 in. (5 x 10 cm) lumber, long enough to rest across. the top of the form, is used to level the top of the concrete before the final finish. A wood float is used to finish the surface of concrete after it is struck off. A steel (hand) float or trowel is used for a smoother surface finish. A Darby and a bull float are also used for smoothing and finishing the concrete. For making and finishing joints in floor slab sidewalks, and pavements, a groover is used. To finish the edge of a slab, an edger is used. To help to distribute the weight over the fresh concrete a knee board, made from lumber and plywood [24 x 12 in. (60 x 30 cm)], is used.

3.6.3 Types of Finishes

A number of finishes can be obtained in freshly placed concrete. Variation in texture and finish is limited only by the imagination and skill of the craftsperson. It can vary from smooth and polished appearance to a rough gravel look.

A *smooth finish* is obtained by using a finishing or steel trowel on the surface, which is quite hard. A swirl float or *trowel finish* is produced for visual interest and surer footing by working the float (wooden, aluminum, or canvas resin) flat on the surface in a swirling motion using pressure. The result is a surface with a fine-textured mattelike finish.

Broom finish is an attractive nonslip texture obtained by pulling a damp broom across freshly troweled surface. It is suitable for traffic areas such as driveways and sidewalks. For best results the broom should be rinsed in water and tapped to remove excess water after each pass. A *rock salt finish* is produced by sprinkling rock salt (coarse gradation) on the surface of troweled concrete surface, which gives a decorative surface finish. After 5 days of curing under waterproof paper the surface is washed off with water and brushed to dislodge or dissolve the salt grains, leaving pits or holes on the surface.



Jointing tool

Darby

Edger

Float

Finish trowel

Square shovel

Figure 3.7 Concrete tools.

A finish similar to some finishes used on cut stone is done through mechanical spalling and chipping with a variety of hand and power tools. This technique, called *brushhammering,* involves removing a layer of freshly hardened concrete while fracturing the aggregate at the surface. The finish can vary from a light scaling to a deep and bold texture achieved with the help of jackhammering with a single-pointed chisel. An *exposed aggregate finish* is one of the most popular and decorative finishes for concrete slabs, patios, tilt-up panels, and sidewalks.

3.6.4 **Curing**

Curing is the process of maintaining enough moisture in concrete to maintain the rate of hydration during its early stages. Unless the concrete is cured properly, it will not achieve the desired properties, such as compressive strength, watertightness, and durability.

When cement comes in contact with water it begins to set. Final set is the stage at which concrete loses its ability to be made into different shapes and becomes a hard mass. After concrete becomes sufficiently hard to hold its shape, the hardening period begins. As it hardens, concrete gains in strength. The entire process .is termed hydration, which was explained in Section 3.5.

The process of hydration in a freshly mixed concrete depends on the amount of water available and the ambient temperature. Although a water/cement ratio of about 0.35 is adequate to guarantee hydration of all particles of cement, mixtures with a water/cement ratio of less than 0.5, without an admixture, tend to be very stiff and unworkable. Thus most concrete mixtures in practice are designed with high water/cement ra6os, high enough to maintain the progress of hydration.

But the chemical reaction between compounds of cement and water is not instantaneous and, in fact, will continue for years. Properties of concrete will improve with age as long as conditions are favorable for continued hydration of the cement. The improvement is rapid in the beginning but continues, more slowly, for an indefinite period of time.

Figure 3.8 shows the rates of strength development in a properly cured concrete and in concrete that is left to dry out. Since the hydration is a continuous process, requiring the presence of water, any loss of mixing water from the concrete signals a slowdown or stoppage of the reaction. Laboratory studies have verified that the concrete must be maintained at humidity over 80% if hydration has to proceed at an appreciable rate. As a corollary, below about 80% humidity, hydration ceases.

Concrete that is made outside a laboratory surroundings will be subjected to heat and wind, which can dry out the moisture from inside the pores. If this loss of water from evaporation or absorption from the surrounding dry ground is not compensated, the

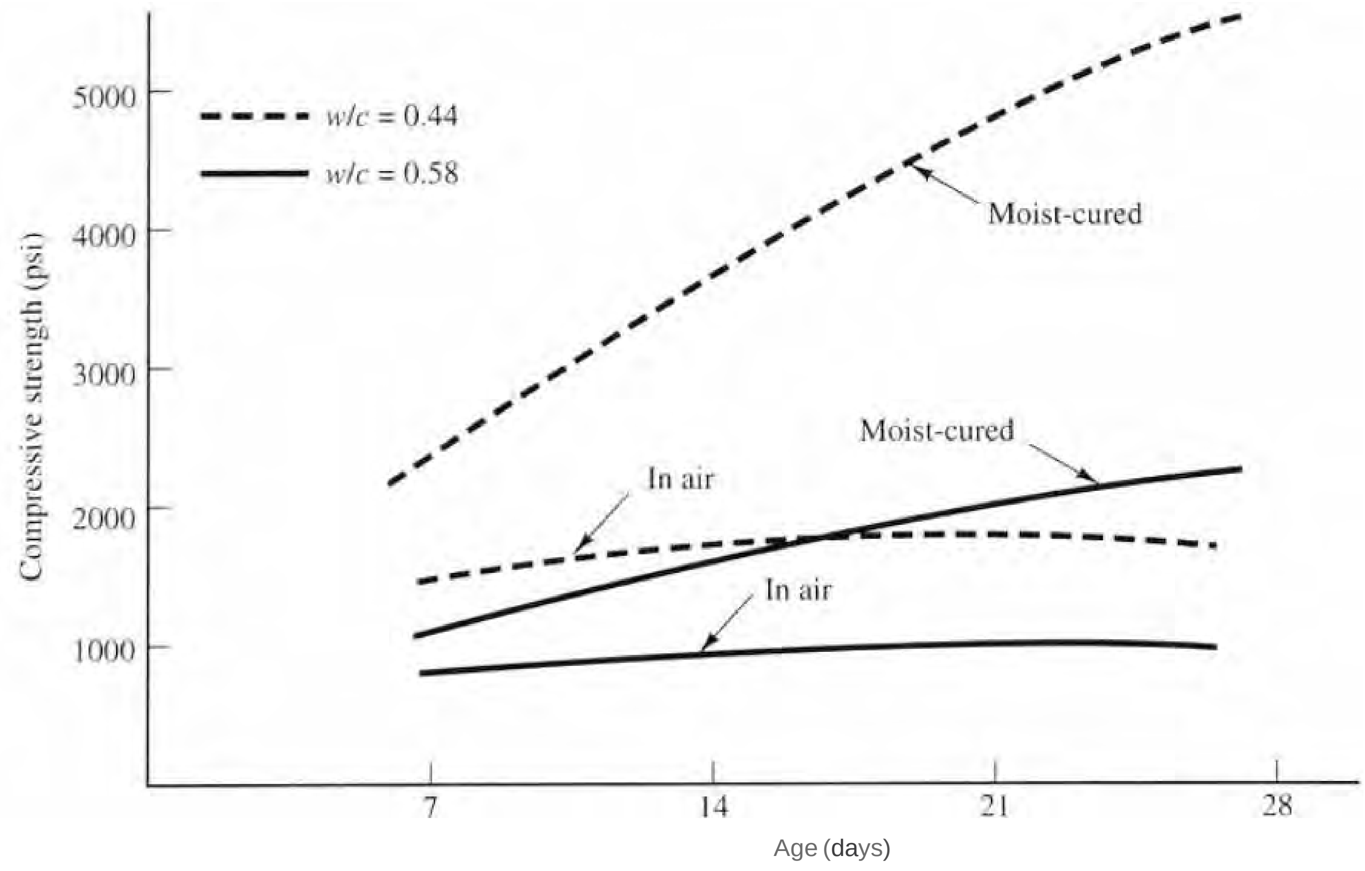


Figure 3.8 Rate of strength development in concrete (based on tests using 3 X 6-in. cylinders).

hydration cannot continue. Curing is a process in which evaporation loss from newer concrete is minimized or compensated.

3.6.5 Methods of Curing

The best method of curing is to substitute for the loss of moisture by keeping the concrete continuously wet by either ponding, fog spraying, or sprinkling, with or without the use of a cover such as burlap and plastic sheet. *Ponding* is accomplished by building earth or sand dikes around the perimeter of the slab to retain a pond of water without the enclosed area. The method requires considerable labor and supervision, and may not be practical except for small jobs.

Fog spraying or *sprinkling* is an excellent method of curing when the temperature is above freezing. This method is costly and requires an adequate amount of water. In addition, a process should be in place to prevent the concrete from drying out between applications of water.

In addition to these methods, covering the concrete with wet burlap, wet cotton mat, and a 2-in. layer of moist sand, earth, hay, or sawdust (wetted once a day) can be an effective curing technique for pavements and floors. *Wet coverings* such as burlap and cotton mats are used extensively for curing concrete. Burlap must be free from any substances that are harmful to concrete or cause discoloration. The moisture-retaining fabric should be kept continuously moist so that a film of water remains on the surface throughout the curing period.

Concrete cured using any of the foregoing techniques is called *moist-cured* or *water-cured* concrete. Water curing may be impractical and expensive in countries where labor is costly because watering should be done two to three times a day. Consequently, other methods of curing have been developed and practiced, although they are less efficient than the conventional method. These methods, developed to *minimize* evaporation loss, include covering with *plastic film,* or *plastic sheet* waterproof paper, and most commonly, providing a liquid membrane-forming compound.

Waterproof paper (or plastic film, impervious sheeting) should be applied as soon as the concrete has hardened and after the concrete has been thoroughly wetted. The sheeting should lay directly on the concrete surface and overlapping edges should be a minimum of 12 in. This method of curing has the important advantage that periodic additions of water are not required. Black plastic film is satisfactory under nonnal conditions, but white film is good in hot weather, as it reflects the sun's rays.

Liquid curing compounds or *liquid ,membrane-forming compounds* (also called seal coats) are used most often because of their versatility, ease of application, convenience, and economy. These compounds are relatively inexpensive and provide an effective means of preventing evaporation from flat slabs and pavements, assuming that they are applied as soon as the concrete is finished.

Most of the compounds have a resin in a solvent. After the application, the solvent evaporates, leaving behind a thin continuous film of resin on the surface of concrete, which seals in most of the moisture. This film remains intact for about a month after which it becomes brittle under the action of heat and then peels off. The curing compounds should not be applied to a dry surface because a dry surface may absorb the compound, which causes strains. If proper care is taken in the selection of the most appropriate compound, it can be very effective. It is also important to make sure that the selected compound is nontoxic, and that its composition does not restrict its use for outdoors only.

Certain curing chemicals can make the surface slippery, presenting a safety issue. The compounds may prevent satisfactory bonding between the hardened concrete and any new concrete or finish that may subsequently be applied. They are not recommended in late fall *in* places where deicers are used to melt ice and snow, as their application may prevent proper air drying of the concrete. (Air drying is necessary to enhance the resistance of concrete to scaling before the application of deicers.)

The curing compounds are generally applied by either brushing, rolling, ot spraying, depending on the circumstances of a particular job. Most of them are applied immediately after the finishing of the concrete, when the concrete is still wet. The compounds should be applied in two coats, in a continuous operation, with the second coat at a right angle to the first.

3.6.6 Effects of Temperature

The length of the curing period depends on such variables as atmospheric conditions (relative humidity and temperature), type of work, characteristics of concrete, and expected strength. The longer the curing period, the greater is its final strength. Concrete kept moist under normal curing conditions will develop about 75% of its final strength in about 28 days. In the majority of construction, concrete is kept continuously moist for a minimum of 7 days after casting.

Hydration of cement is also dependent on the ambient temperature. In addition to keeping moist, curing should also assure that the concrete remains warm. The temperature range considered most desirable with the conventional method of curing is 70 to 90° F (21.6 to 32.2°C).

The temperature at which concrete is cured affects the development of its strength with time. The rate of gain in strength increases with increase in curing temperature. *Steam curing* is one of the curing techniques in which hydration rate is increased by supplying steam, generally under pressure. Precast concrete sections and concrete masonry blocks can reach 70% of their normal 28-day strength when subjected to properly controlled wet steam curing (at about 150° F or 65.5° C) for about 15 hours. Full 28-day compressive strength can be achieved by steam curing for 24 hours.

Two methods of steam curing are employed for early strength development. Curing in live steam at *atmospheric pressure* is used for enclosed cast-in-place structures, and curing using *high-pressure steam autoclaves* is utilized for small manufactured units. The former is done in a steam chamber or other enclosures, such as tarpaulins, to minimize moisture and heat loss. The steam is applied at least 2 hours after final placement of concrete. The maximum steam temperature inside the enclosure should not exceed 180° F (83° C). High-pressure steam curing in autoclaves takes advantage of higher temperatures, in the range 325 to 375° F (160 to J 90° C). Hydration is faster at elevated temperatures and pressures.

Proper curing of concrete will improve its quality and performance. Apart from being stronger and more durable, the concrete is also more resistant to traffic wear and less permeable. In winter months no curing may be necessary since the rate of evaporation is very low in a cold, moist atmosphere.

3.7 PROPERTIES OF HARDENED CONCRETE

The properties of fresh concrete described earlier are important only for a few hours after the mixing, beyond which, for the remainder of the life of the structure, properties of hardened concrete dominate the scene. The important properties of hardened concrete are:

- Strength
- Modulus of elasticity
- Durability
- Creep
- Shrinkage
- Watertightness or impermeability

Of these, compressive strength is generally considered to be the most important because of the more common application in reinforced concrete construction and the dependency of most other properties on the compressive strength. But there are many situations where other properties are significantly more important than the compressive strength. For example, durability should be the most important consideration in designing concrete for use in pavements. Similarly, watertightness is the most important property for water-retaining concrete structures. Although an increase in the strength property of concrete will generally improve all the other properties, there are exceptions to this rule. For example, an increase in the quantity of cement will increase the compressive strength, but it may make the concrete less resistant to freeze-thaw cycles. Thus the attainment of the maximum strength should not be the sole criterion in the design of concrete mixtures.

In general, properties of hardened concrete depend on:

- Mix proportions
- Curing conditions
- Environment

The role of curing was discussed earlier. Curing is a process of maintaining the rate of hydration, without which the hardened concrete will not attain any of the desired properties. The environmental factors influence the strength gain, shrinkage, and other properties. An offshore concrete structure may not be as durable as a similar structure built on land. Concrete structures built on soil (such as slab on grade) may deteriorate faster than those above ground. The mix proportions, which deal with type and amount of ingredients, affect all properties of concrete (discussed later).

The following sections deal with various properties of concrete and parameters that influence them. It should be remembered that dry cement does not possess the cementing or binding property; chemical reaction between cement and water-the hydration-yields products that provide the binding property after hardening.

3.7.1 Compressive Strength

The *compressive strength.* is the most important property of hardened concrete and is generally considered in the design of concrete mixtures. Although concrete can be manufactured to have a compressive strength as high as 12,000 psi (82.7 **MPa),** in ordinary construction a strength in the range 3000 to 6000 psi (20.7 to 41.4 MPa) can be expected. Cast-in-place construction generally uses concrete of strength closer to the low range, whereas precast construction, which routinely follows a rigorous quality control program, makes use of concrete of strength closer to the high range.

It is customary to estimate the properties of concrete in the structure from compression tests on specimens made from fresh concrete as it is placed and cured in the standard manner. Cylindrical specimens of 3, 4, or 6 in. diameter (7.5, 10, 15 cm) and height equal to two times the diameter, and 2-, 4-, and 6-in. (5-, 10-, and 15-cm) cubes are used. Since the compressive strength is affected by many variables which include the environmental factors and the curing conditions, the actual strength of the concrete (in the structure) will not be the same as the strength of the specimen.

A number of factors, such as amount of cement, amount of water, types of ingredients, mix proportions, curing, temperature, age, size and shape of specimen, and test conditions affect the compressive strength. By treating concrete as a conglomerate of particles of different sizes, bonded together by the products of reaction between cement and water, the strength of the matrix can be recognized as a measure of the strength of individual particles and that of the bonding agent. As mentioned earlier, most aggregates used in concrete exhibit compressive strength in excess of 10,000 psi. When the desired strength of concrete is less than the strength of aggregates, which is true in most cases, one can expect the concrete strength to be a function of the strength of the paste or that of the products of hydration. At any given age, the hydration is dependent on the amount of cement and water. But water cannot be treated as a material that possesses adequate strength, and thus it follows that the compressive strength of properly cured concrete at any age is directly related to the amount of cement in the mix.

Figure 3.9 shows the rate of increase in compressive strength with increase in the quantity of cement for typical mixtures of equal consistency (measured with a slump test). The rate of hydration is not the same for all types of cement, and consequently, the strength of concrete is also dependent on the type of cement. Cements containing a higher percentage of tricalcium silicate gain strength much faster than do cements containing more dicalcium silicate. This means that concrete made with type III cement has higher early strength than concrete made with types I and II cement. However, at later ages the difference in strength between type **III** and other cements is very small (Fig. 3.10).

Size and shape of aggregates. Strength of concrete of a given consistency increases with increase in fineness modulus of fine aggregate. *Fineness modulus,* as explained in an earlier chapter, indicates the average size of particles in the graded

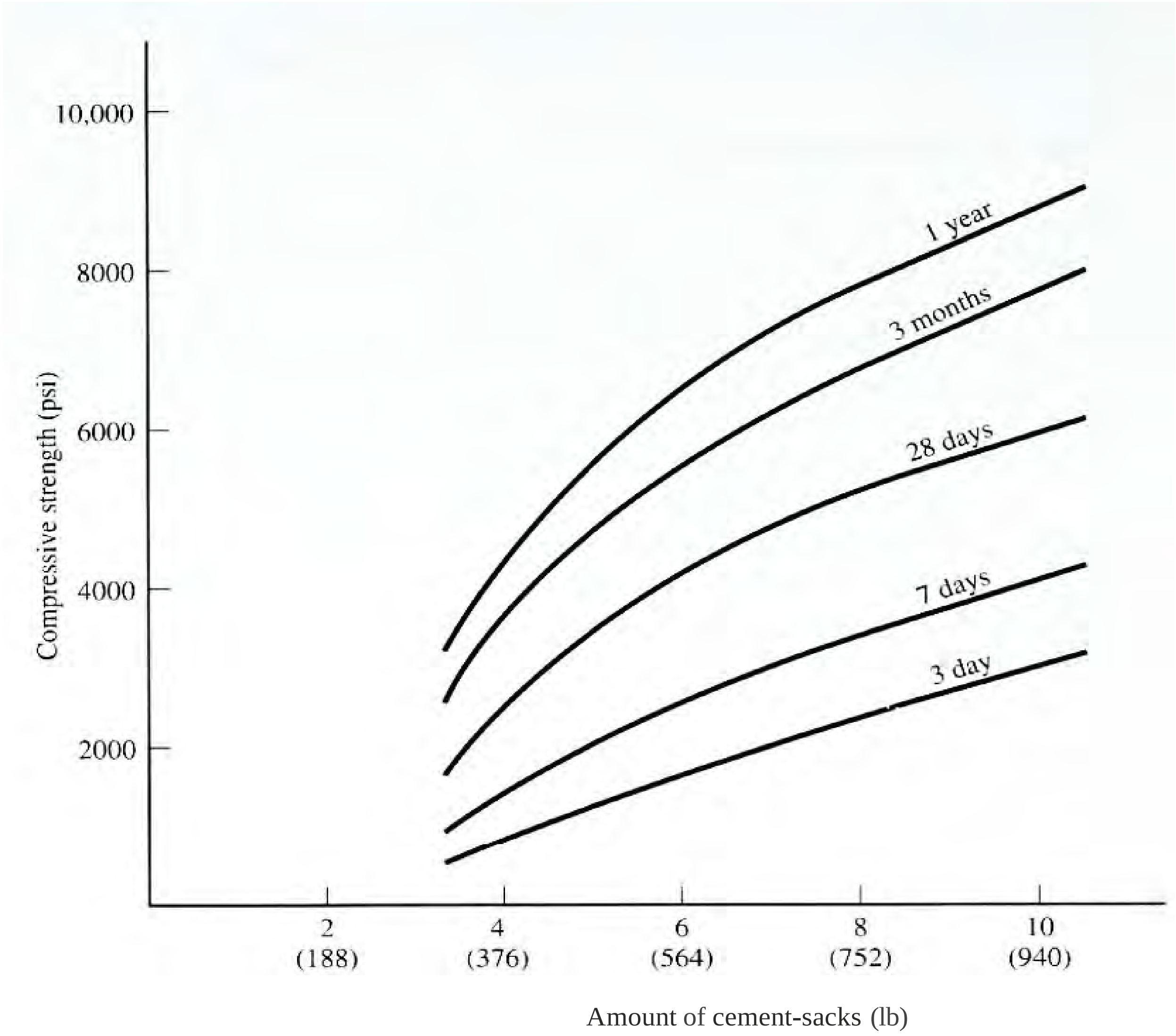
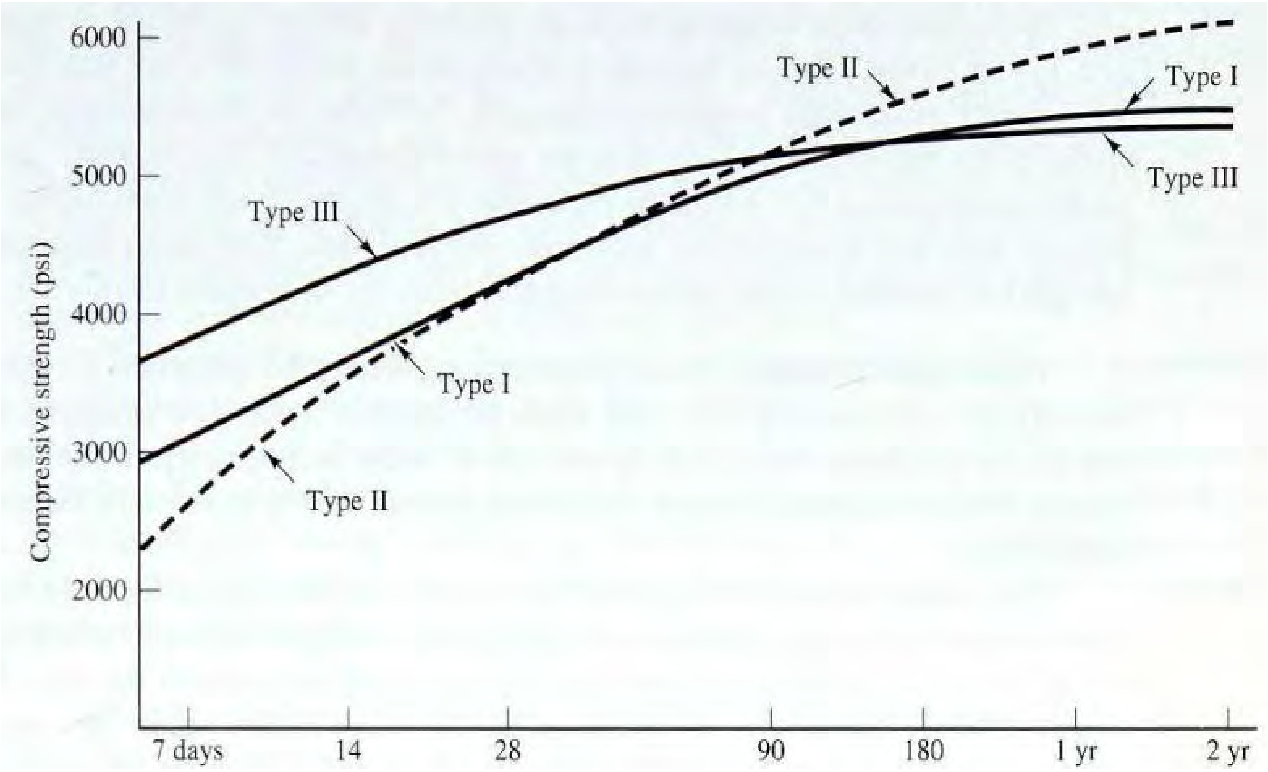


Figure 3.9 Effect of cement content on compressive strength of concrete.

aggregate. A higher number means coarser gradation, and a lower number reflects finer gradation. Fineness modulus of graded sand for use in concrete generally lies between 2.3 and 3.1. Natural sand of fineness modulus less than 1.5 is seldom found. Figure 3.11 shows that as the gradation becomes coarser, compressive strength increases. Beyond a certain value, the mix becomes very harsh, which decreases the strength.

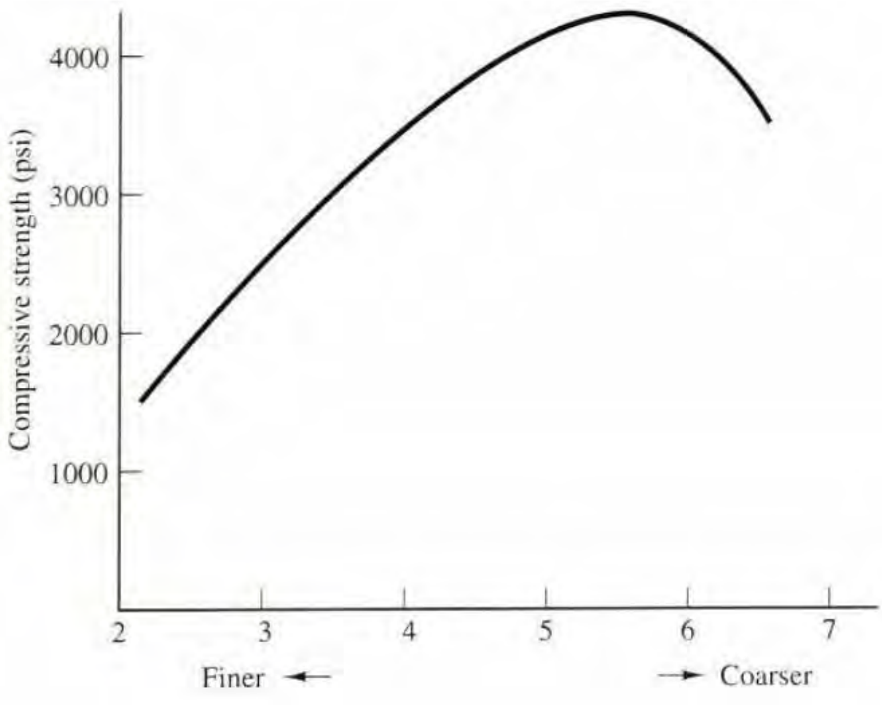
Strength of concrete may also be affected by the type and size of coarse aggregates. Because of their surface texture and particle shape, limestone and granite aggregates, may exhibit compressive strength up to 20% higher than river gravel using the same water/cement ratio. The strength of lightweight concrete is lower than that of normal-weight concrete of equal consistency.

The larger the maximum size of coarse aggregate, the lower the surface area and therefore the lower the water requirement for a set consistency. With a lower water/cement ratio the strength of concrete is increased. However, the use of larger aggregate per se decreases the compressive strength. This is probably due to less surface, which lowers the bond.



Days/years

Figure 3.10 Concrete strength development with time.



Fineness modulus of mixed aggregates

Figure 3.11 Effect of size of aggregates on compressive strength (consistency remaining constant).

Rich mixes (high cement content) are adversely affected by the use of large aggregate. In lean mixes, however, increase in aggregate size lowers the water requirement and may actually increase the compressive strength. Typically, the smallest coarse aggregate produces the highest strength for a given water/cement ratio. For example, at a given water/cement ratio, a ¾-in. (10-mm) maximum size aggregate will yield higher-strength concrete than will a 2-in. (5-cm) maximum size aggregate. With larger aggregate, high strength can be obtained with the use of superplasticizing admixture (Section 3.9.1).

Water/cement ratio. For a given cement content, the maximum strength occurs in a mix that contains only sufficient water for complete hydration. However, this mix may be dry and harsh, and it may be difficult to obtain homogeneity. When the cement content remains constant, strength of concrete decreases with increase in the amount of mixing water.

The compressive strength of concrete is commonly estimated from the water/cement ratio, called *Abram's law* (1918). According to this rule, which is plotted in Fig. 3.12, the compressive strength decreases with increase in the ratio between weight of water and weight of cement, called the *water/cement ratio*. This means that when the cement content is maintained constant and the amount of mixing water is increased, the strength decreases.

Although the water/cement ratio is an important property in the design of concrete mixtures, it should be noted that the same strength cannot be expected with different aggregates, even when the water/cement ratio is kept the same. As an example, for the same water/cement ratio, mortar, which does not have coarse aggregate, is stronger than concrete. However, the water/cement ratio does provide a convenient means of contro11ing the quality of concrete.

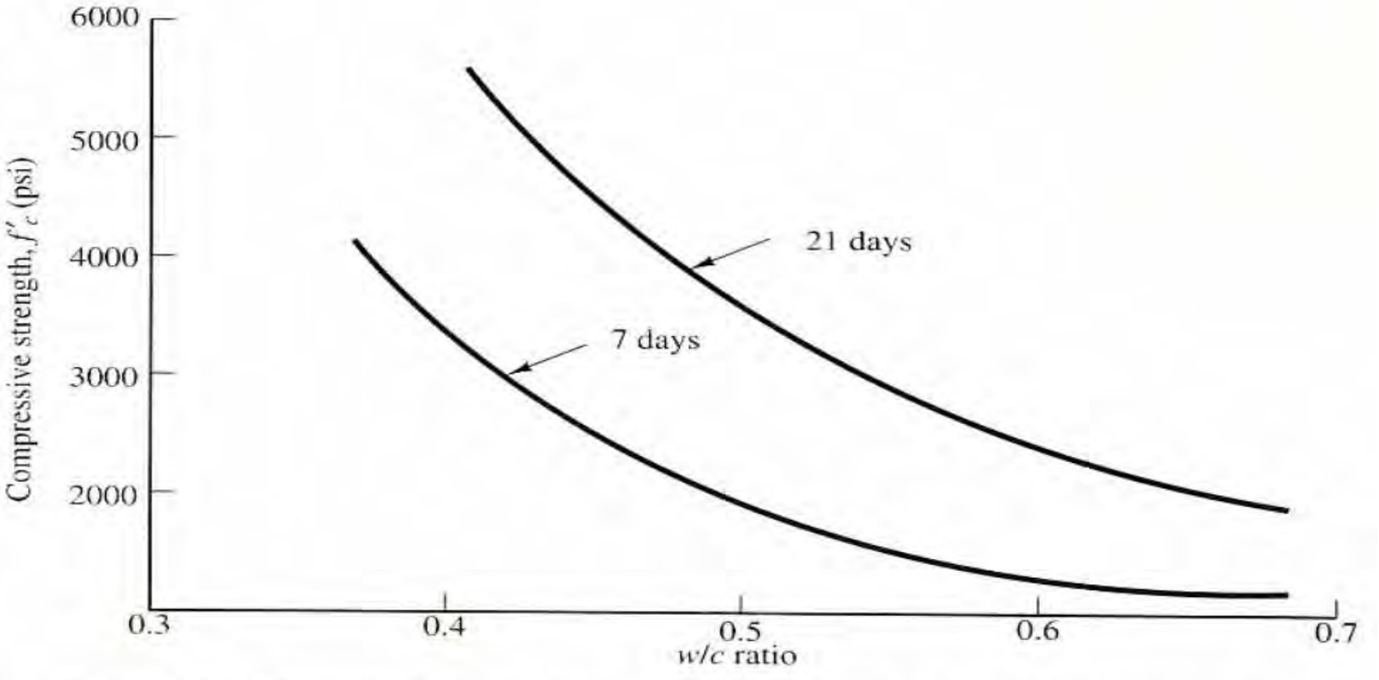


Figure 3.12 Typical relationship between f'_c and w/c ratio at 7 and 21 days (based on tests on water-cured 3 × 6-in. samples).

Voids. Increase in water content increases the voids in concrete, which decreases the durability, watertightness, and of course the compressive strength. Early theories on concrete strength have established a relationship between compressive strength and void content and the void/cement ratio. These relationships are similar to the compressive strength/water-cement ratio relationship and stress the importance of cement content and low void content in achieving good-performance concrete. Thus, it should be understood that good dense concrete requires a sufficient amount of cement plus properly graded aggregates to reduce the void content.

The water content should be enough to guarantee complete hydration of portland cement. Any excess water added to the mix increases the void content, which in tum decreases the quality of concrete. But it should be recognized that insufficient amount of cement means an inadequate amount of binder, and the resulting concrete is definitely of lower quality. In summary, although the water/cement ratio is a convenient way to do mix_ design, good-quality concrete requires a sufficient amount of cement, well-graded aggregates, and a minimum amount of mixing water.

Curing and air entrainment. Strength of concrete increases with age and curing. The effects of length of curing (age) and the temperature on the compressive strength are as shown in Figs. 3.13 and 3.14. Plastic concrete (or fresh concrete) has negligible strength. Strength of concrete at **1** day is about 10 to 20% of its 28-day strength. The 7-day strength is about 70 to 80% of the 28-day strength. It can be seen from Figs. 3.8 and 3.14 that moist-cured specimens continue to gain strength even after several years, but on the other hand, specimens that are left to dry cease to hydrate and gain strength. Improvement in strength beyond a year is very little. Increase in water temperature, both at mixing and curing, makes the strength gain faster. Using steam to cure concrete has a dramatic effect on the strength gain.

Concrete made with air-entraining chemicals, or air-entrained concrete, usually has a lower compressive strength than ordinary concrete. (Air entrainment is discussed in Section 3.9.1.) Entrained air in the amount of 3 to 8%, without adjustment of the water/cement ratio, will reduce the compressive strength by about 5% for each 1% of added air. But in practice, the water/cement ratio and sand content of air-entrained concrete will be decreased to obtain the same strength as that of normal concrete.

Compression test. Jn the United States, the compressive strength of concrete is determined from compression tests on *cylindrical specimen’s* 6 in. in diameter and 12 in. in height (uniaxial compression test, ASTM C469). Empty cardboard or metal cylinders are filled with fresh concrete using a standard procedure. After 24 hours the specimens are taken out of the molds and moist cured for 28 days. At the end of the curing period they are capped and tested in a moist condition. The failure load divided by the cross-sectional area is called 28-day cylinder compressive strength **(/).**

$$f'_c = \frac{p}{(\pi/4)d^2}$$

where P is the failure load and dis the diameter of the cylinder.

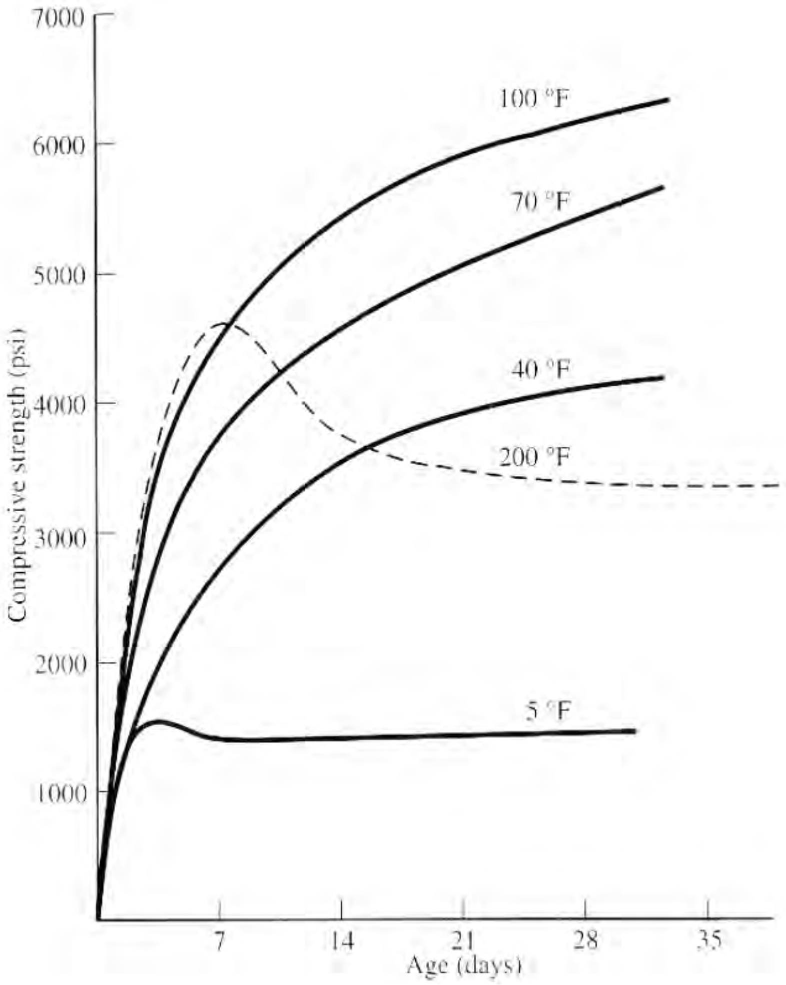


Figure 3.13 Effect of curing temperature On f'_c

The compressive strength thus determined is found to depend on the size of the specimen, the shape of the specimen, and the moisture condition. The greater the ratio of height to diameter, the lower is the measured compressive strength. For specimens of height equal to twice the diameter, the compressive strength decreases with increase in diameter. A 4-in.-diameter cylinder (8 in. in height) exhibits approximately 5% higher strength than does a 6-in.-diameter cylinder (12 in. in height).

The moisture content of specimens affects the compressive strength. Air-dried specimens (at the time of testing) are shown to possess more compressive strength than that of saturated specimens, on the order of 20 to 25%. The strength is also affected by the speed of testing-a slower rate will show a lower strength. In the laboratory the rate of loading is adjusted so that failure takes place within 2 to 3 minutes.

3.7.2 Tensile Strength

The tensile strength of concrete is important to resist cracking from shrinkage and temperature changes. *Direct tensile strength* measurements are difficult and are not usually clone. It is common practice to assess tensile strength using either the flexural or split cylinder test.

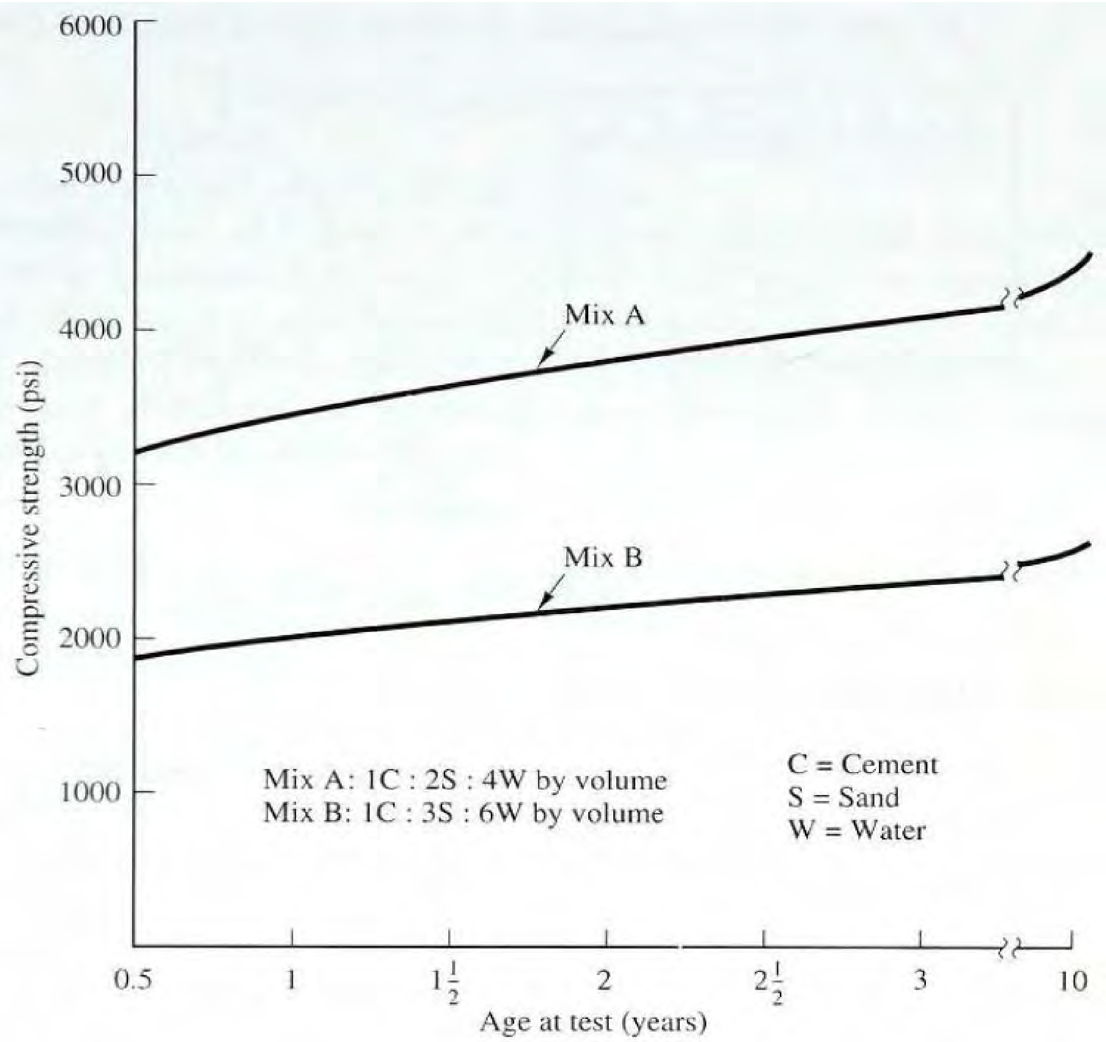


Figure 3.14 Effect of age on compressive strength of concrete. (Based on University of Wisconsin tests, *Journal of the American Concrete institute* . Vol. 27. Feb. 1943.)

In the *split cylinder test* (ASTM C496), the cylindrical specimen (placed with its axis horizontal) is subjected to a line load (uniform) along the length of the specimen (Fig. 3.15). Using the load at which the specimen splits into two, P, the tensile strength, f_t, can be calculated:

$$f_t = \frac{2P}{\pi l d}$$

where l is the length of the cylinder and d is the diameter of the cylinder.

The tensile strength of concrete increases with increase in its compressive strength. The splitting strength is about 10 to 15% of the compressive strength; the lower the compressive strength, the higher the percent. Variation of tensile strength with water/cement ratio is similar to that of compressive strength. With increase in the fineness modulus, or as the gradation becomes coarser, the tensile strength increases. The tensile strength is also affected by the type and shape of coarse aggregate particles.

The tensile strength of concrete can also be measured using flexural specimens. Details of the flexural test are shown in the next section. The *flexural strength* is 40 to 70% higher than the splitting tensile strength.

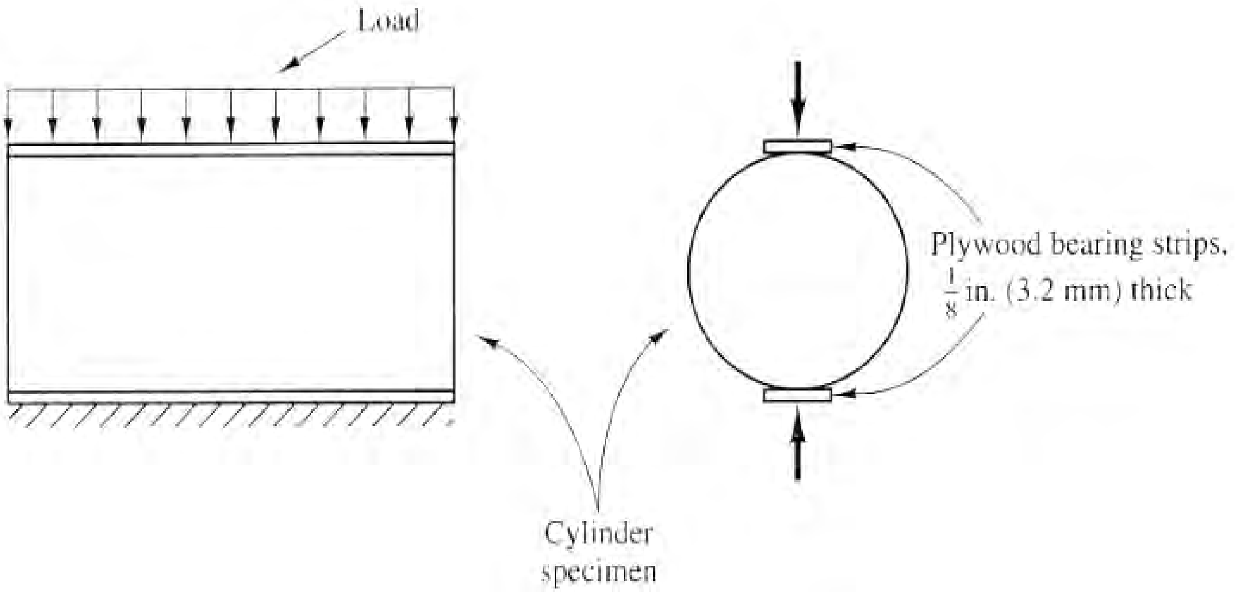


Figure 3.15 Split cylinder test.

3.7.3 Flexural Strength

A flexure test is the most common procedure used to measure the tensile strength of concrete. In this test a concrete beam with span equal to three times its depth is subjected to *third-point loading* (ASTM C78). This results in tensile stresses at the bottom and compressive stresses at the top of the beam. Since concrete is weaker in tension, the specimen fails with a flexural crack near the section of maximum moment. The failure load is used to determine the tensile strength, called the *modulus of rupture* (MOR), with the help of the bending equation (Fig. 3.16):

$$\text{bending stress} = \frac{Mc}{I}$$

where M is the maximum moment, I the moment of inertia, and c the distance from the neutral axis to the extreme fiber in tension.

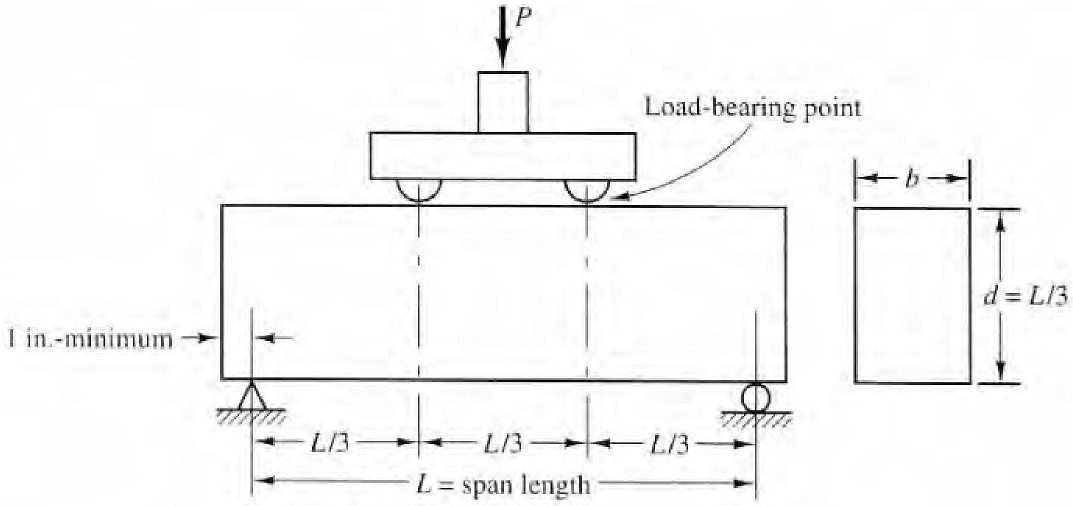


Figure 3.16 Flexure test (third-point loading).

For a rectangular section of width b and depth d, the bending stress or modulus of rupture in a third-point loading specimen, using the equation above, is

$$\text{modulus of rupture } \textbf{(MOR)} = \frac{Pl}{bd^2}$$

where/ is the span length and P is the failure load.

The modulus of rupture is affected by the water/cement ratio, the age at test, and the curing condition as shown in Fig. 3.17. Laboratory tests have shown that the lowest MOR belongs to concrete made with aggregate of lowest flexural and bond strengths. Typically, MOR is about 10 to 23% of the compressive strength of concrete; the lower the f'_c the higher the percentage. The following empirical relationship is commonly used to predict the MOR (Fig. 3.18):

$$\text{MOR} \qquad 12\sqrt{f'_c}$$

where MOR *andf'c* are in psi. The flexural test overestimates the tensile capacity of concrete because the propagation of a crack (originated at the extreme fiber in tension) is blocked by the less stressed material nearer the neutral axis.

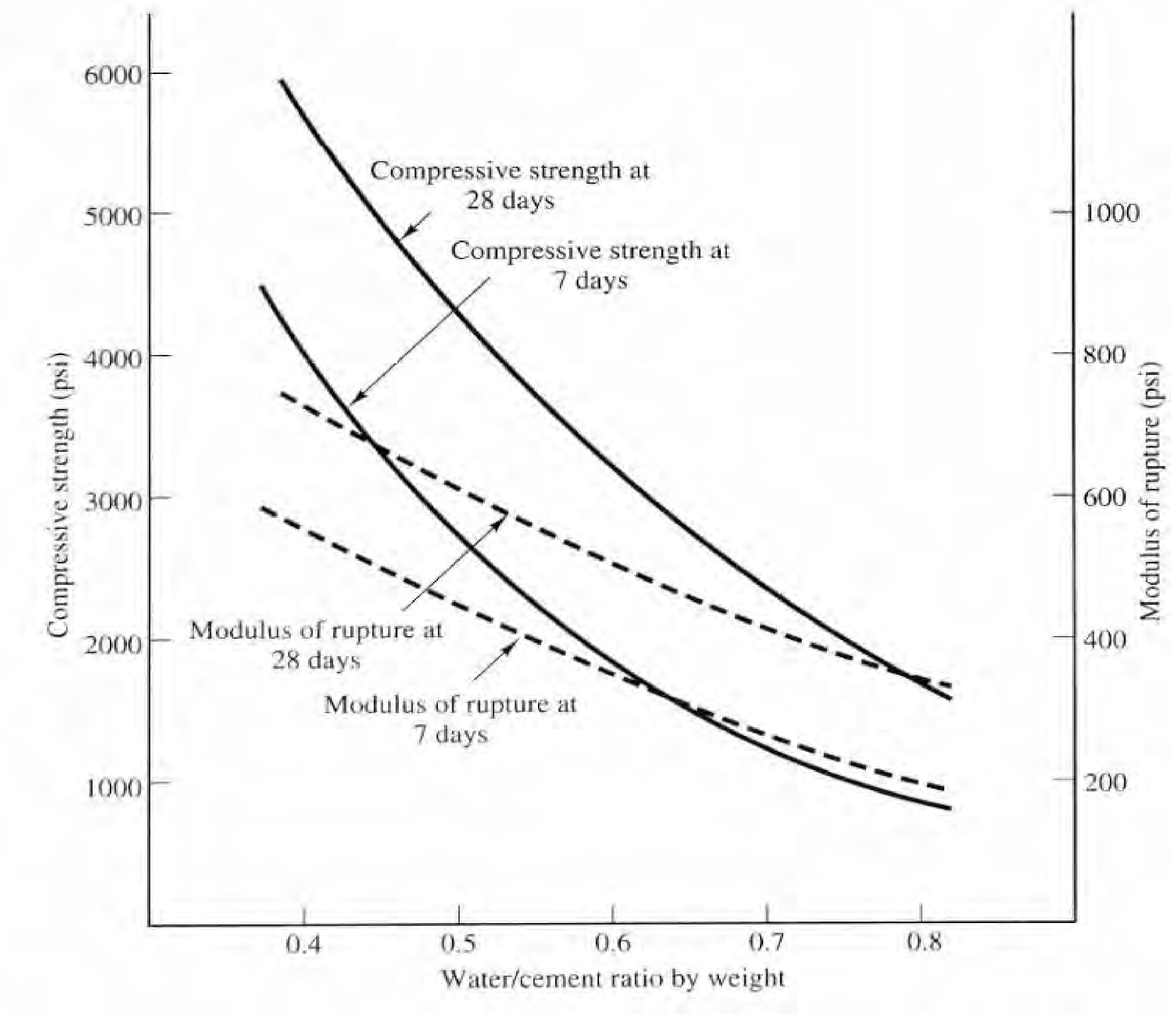


Figure 3.17 Typical variation of concrete strengths with water/cement ratio.

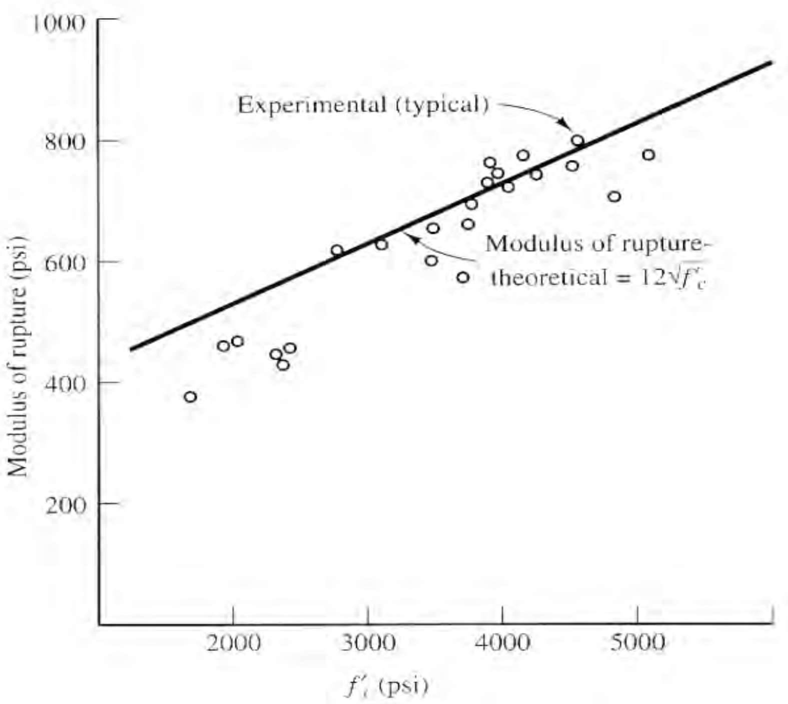


Figure 3.18 Relationship between compressive strength and modulus of rupture.

3.7.4 Stress-Strain Diagram and Modulus of Elasticity

Figure 3.19 shows a typical stress-strain diagram for concrete in compression. It consists of an initial elastic range, followed by a nonlinear increase in stress with increase in strain up to a maximum stress, beyond which the stress decreases until failure at a maximum compressive strain. Various concretes exhibit different stress-strain relationships, but the shape of the diagrams, and thus their characteristic, are the same.

Figure 3.20 shows typical stress-strain diagrams for various concretes. It can be seen that, with increase in the compressive strength of concrete, the elastic portion of the curve becomes larger and the failure is more brittle. Although the failure strain (maximum strain) is dependent on the type of concrete and its strength, it is generally taken to be a constant value of 0.003.

It should be noted that the two components of concrete, cement paste and aggregate, when tested individually in compression, exhibit a linear stress-strain relationship, the aggregate possessing higher modulus and strength than the paste. The explanation for the nonlinear stress-strain relationship in concrete lies in the development of microcracking in the interfaces between the aggregate and the paste. The shape and surface characteristics of aggregate particles also influence the shape of the stress-strain curve.

The *modulus of elasticity,* or *Young's modulus,* is the constant of proportionality between stress and strain. It can only be applied to the straight-line portion of the stress-strain diagram. When no straight-line portion is present, or beyond the elastic limit, the modulus of elasticity can be interpreted to measure the slope of the tangent to the curve at a point on the diagram.

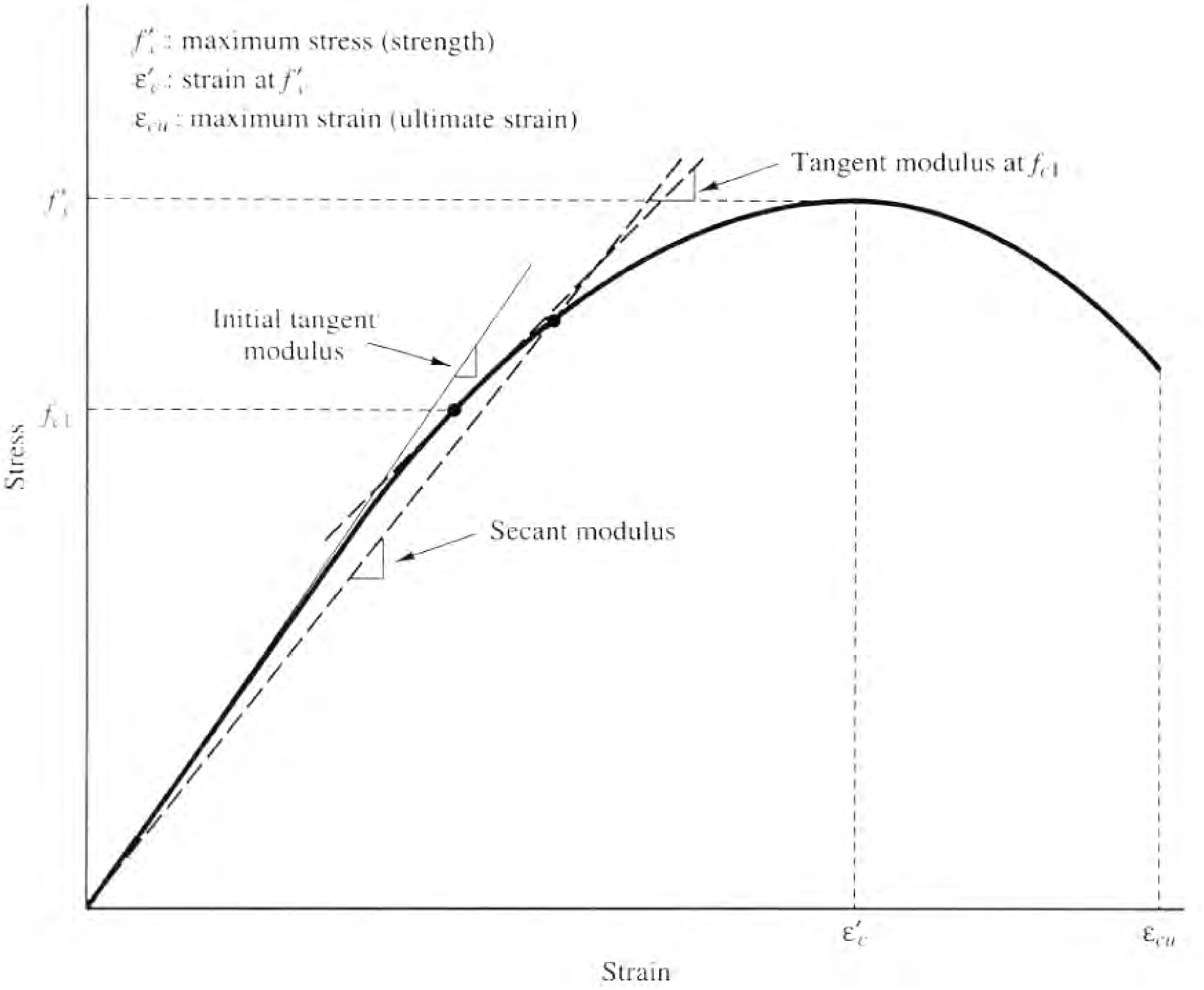


Figure 3.19 Typical stress-strain diagram of concrete.

When the modulus of elasticity is used to measure the slope of the straight-line portion of the diagram or the slope of a tangent to the diagram, it is called the *tangent modulus*. When the tangent modulus is measured as a tangent to the curve at its origin, it is referred to as the *initial tangent modulus*.

The modulus of elasticity can also be measured as the slope of a line connecting two points on the curve, which is called the *secant modulus*. The modulus of elasticity most commonly used is the secant modulus, as the initial tangent modulus, measured at the origin of the curve, may not be accurate due to errors in reading very small strains at the start of the test. Because the secant modulus decreases with increase in stress, the stress at which the modulus has been determined (upper limit) should always be indicated. According to ASTM (C469), the modulus of elasticity of concrete, E, can be calculated as follows:

$$E = \frac{S_2 - S_1}{\varepsilon_2 - 0.00005}$$

where S_2 is the stress corresponding to 40% of ultimate load, S_1 the stress corresponding to a strain ε_1 (50 millionth inch per inch), and ε_2 the longitudinal strain produced by stress S_2.

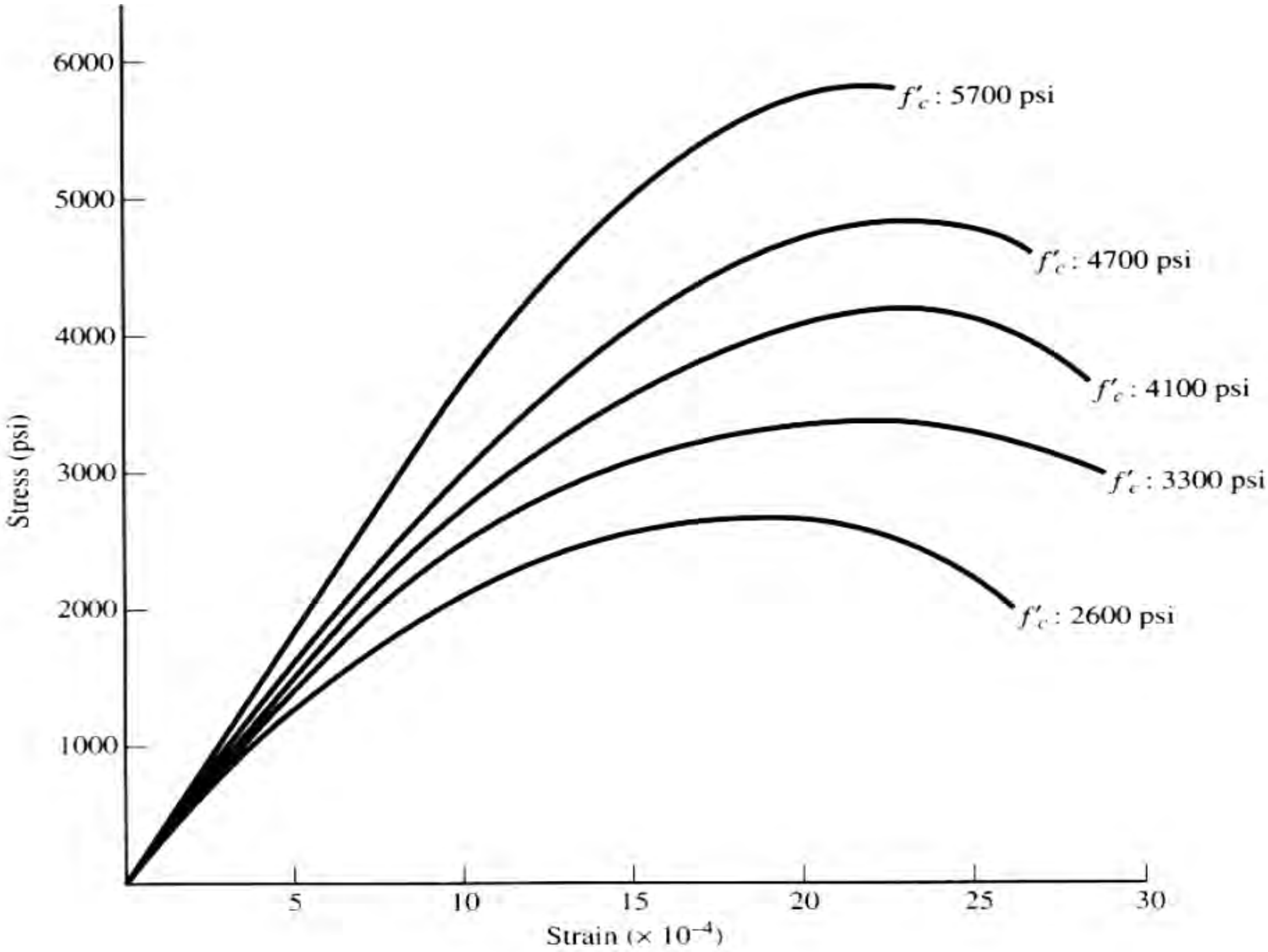


Figure 3.20 Stress-strain diagrams of various concretes (based on 3 X 6-in. cylinders).

The modulus of elasticity of concrete increases with its density, age, and strength. At a given strength, the elastic modulus is largely dependent on the aggregate used and the age at test. Typically, it falls between the modulus of elasticity of plain rocks and that of mortar. The larger the amount of coarse aggregate of elastic modulus higher than that of concrete, the greater would be the modulus of elasticity of concrete. Concrete made with expanded clay aggregate (lightweight aggregate) has a much lower modulus of elasticity than that of concrete made with gravel aggregate. In general, modulus of elasticity of lightweight concrete is 40 to 80% of the modulus of normal-weight concrete.

According to ACI (318), the modulus of elasticity of concrete can be calculated as follows:

$$E = w^{1.5}(33) \times f'_c{}^{(0.5)}$$

where Eis the modulus in psi, *w* the unit weight of concrete in pcf, andf'c the compressive strength of concrete in psi. For normal concrete the equation above simplifies to

$$E = 57{,}000 \times f'_c{}^{(0.5)}$$

Figure 3.21 shows the relationship between the modulus and compressive strength. The tension modulus, determined from the tension tests, is nearly the same as the compression modulus.

Example 3.1

Estimate the tensile strength, the modulus of rupture, and the modulus of elasticity of normal concrete with $f'c = 3500$ psi.

Solution The average density of normal concrete is 145 pcf. The tensile strength/compressive strength ratio varies with the water/cement ratio, decreasing with decrease in the water/cement ratio. The splitting tensile strength ranges from 0.07 to 0. IO times the compressive strength.

Estimated splitting tensile strength = 0.1(3500)
= 350 psi
Modulus of rupture = I2(f'c)0.5
= $12(3500)^{0.5}$
= 710 psi
Modulus of elasticity = 57,000(f'c)0.5
= 3.37×10^6 psi

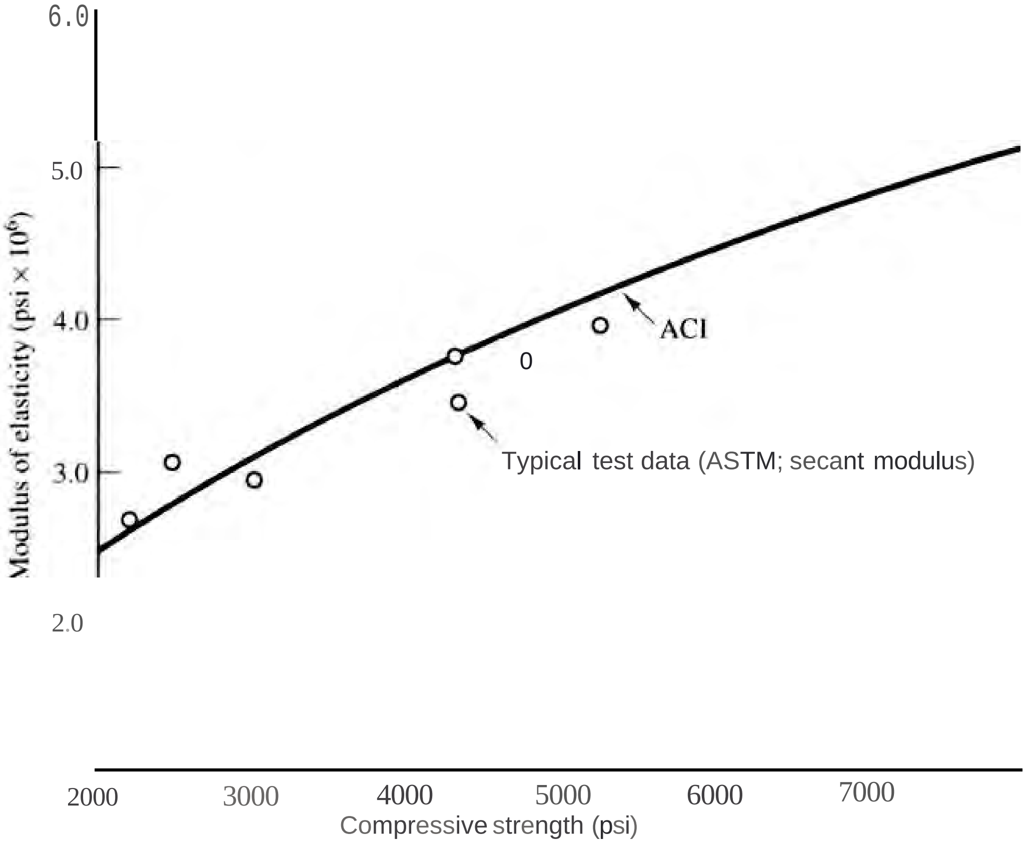


Figure 3.21 Variation of modulus of elasticity with compressive strength of normal-weight concrete.

3.7.5 Shrinkage

Concrete has the greatest volume at the time of mixing or when it is placed in forms. Following the setting, the concrete slowly decreases in volume or shrinks. *Shrinkage* or volume reduction in concrete is the result of settlement of solids and the loss of water.

When concrete is still plastic, aggregate particles settle down, displacing water and air to the top. With help from the environment, the water on the surface gets evaporated. Both of these processes-settlement of solids and evaporation of water from the fresh mix-result in shrinkage of wet concrete. This reduction in volume in plastic concrete (before the concrete sets) is called *plastic shrinkage.* Shrinkage that is due to drying of hardened concrete is called *drying shrinkage.*

Plastic shrinkage. When portland cement reacts with water, the system-cement plus water-undergoes a net reduction in volume. But it should be noted that the volume of solid matter (products of hydration) increases. The volume of saturated cement gel is about 2.2 times that of dry cement. This means that cement paste sealed in a glass tube, with excess water on top, may eventually expand enough to crack the glass tube. (Cement paste stored in water may expand up to 0.1% in 3 months.)

But when concrete is stored in water for only short periods, at different intervals, the initial shrinkage or reduction in volume exceeds any subsequent expansion in water. But concrete that is continuously stored in water increases in dimension. With prolonged storage in water, the expansion of concrete is about 0.01 to 0.02%. On the other hand, concrete that is allowed to dry decreases in volume. On subsequent wetting, it expands, but the increase in volume is less than the initial decrease.

The decrease in volume of the cement-water system (plastic concrete) is the plastic shrinkage or initial shrinkage. When the plastic concrete is allowed to dry quickly, it aggravates plastic shrinkage and leads to surface cracking. These cracks look like short irregular cracks on the concrete surface.

Plastic shrinkage that takes place during the first day after mixing can be 5 to 10 times the drying shrinkage and is thus very important in crack formation. These cracks occur mostly in horizontal surfaces, usually at the time when water sheen disappears from the surface.

Plastic shrinkage is more common in slabs and pavements, as the large surface area contributes to high evaporation loss. When the evaporation loss from the surface of concrete is faster than bleeding, fresh concrete dries rapidly. As a result, the tensile stresses on the surface can augment plastic shrinkage cracks. Hot weather conditions increase the plastic shrinkage due to excessive evaporation loss. A large amount of plastic shrinkage will result in premature cracking (before the surface hardens) and will affect concrete durability.

The amount of plastic shrinkage depends, largely, on:

- Type of cement
- Water/cement ratio
- Quantity and size of coarse aggregate
- Consistency of the mix

Stiffer mixes have lower initial shrinkage than that of flowable concrete. Wet mixes settle longer than dry mixes, and thus shrink more than dry mixes. Dry spots on the subgrade will pull more water out of fresh mixes, which leads to differential settlement of aggregates.

A reduction in temperature of the fresh mix lowers the amount of plastic shrinkage. A decrease in cement temperature of 8 to 10°, water temperature of 4°, or aggregate temperature of 1.8° will lower the concrete temperature by about 1°. Thus it is easier to cool the aggregates and/or mixing water to attain a lower temperature in concrete.

A number of techniques can be managed to minimize plastic shrinkage cracks. Revibration prior to floating will prevent the development of plastic shrinkage cracking. Spraying cold water on aggregates before mixing and using cold water for mixing may offset the onset of plastic shrinkage cracking. Concrete can be cooled by as much as 10°F (6°C) if the mixing water is chilled. If ice (crushed or flaked) is incorporated into the mix water, the concrete can be cooled by as much as 20°F (11°C). Any procedure that minimizes or eliminates evaporation loss will decrease plastic shrinkage. Erection of sunshades and windbreaks will help. Evaporation loss can also be minimized by spraying a curing compound or covering the concrete with wet burlap or plastic sheets. Water-reducing and air-entraining admixtures are helpful in reducing plastic shrinkage cracks.

Crazing, which is a hexagonal pattern of surface cracking at an early age in concrete, is due primarily to improper finishing and curing. Excessive floating and troweling is a major cause of crazing. Such finishing procedures bring excessive amounts of cement, water, and fines to the surface. Consequently, the surface layer becomes weak, and aided by excessive evaporation loss, the top of concrete cracks.

Drying shrinkage. Drying shrinkage, which occurs in hardened concrete, is attributed to the loss of water from cement gel, and can be as large as 1500×10^{-6}. The average drying shrinkage can be taken as 500×10^{-6}, or 0.05% of its length (about $\frac{1}{16}$ in. per 10 ft of length or, 1.5 mm per 3m of length), and shrinkage for most concrete is in the general range 350 to 650×10^{-6}. This means that a slab 30 ft by 80 ft will shrink in the range of 0.12 to 0.23 in. in the short direction and 0.34 to 0.62 in. in the long direction. When this shrinkage is restrained, it results in cracking. Provision of control joints will minimize these cracks. It should be emphasized that it is not shrinkage but restraint to shrinkage that causes cracking.

Drying shrinkage is gradual. The rate of shrinkage decreases with time. About 40 to 80% of 20-year shrinkage occurs within 3 months. At the end of one year, the rate of shrinkage drops down to nearly one-half the initial value. Note that when concrete that is allowed to dry comes in contact with moisture, it swells. Similarly, concrete that is stored in 100% relative humidity does not shrink; instead, it swells.

Drying shrinkage depends on a number of factors, such as type of cement, amount of cement, mix proportions, size and shape of structure, curing, environmental conditions (temperature and humidity), and reinforcement. When the water/cement ratio is increased, drying shrinkage increases. Increase in water/cement ratio of 100% (from 0.35 to 0.70) may increase the shrinkage three to four times.

Decrease in maximum size and quantity of coarse aggregate increases the amount of drying shrinkage. An excessively high content of sand will significantly increase the shrinkage. On the other hand, using too much coarse aggregate will restrain shrinkage deformations and result in excessive tensile stresses. Hard aggregates offer increased resistance to compression and enhance the restraint to shrinkage of cement paste, thus lowering the amount of shrinkage. Generally, shrinkage of normal-weight concrete is less than that of lightweight concrete. Concrete made with gravel and sandstone shrinks more than that made with granite or limestone. Mixtures with highly absorptive aggregates shrink more, and with high-density low-absorptive aggregates shrink less.

As the cement content increases, the shrinkage as well as the cracking tendency will increase. A decrease in humidity leads to rapid moisture loss and increase in shrinkage. However, the most important factor that affects shrinkage is the amount of aggregates. Typically, mortar shrinks three times and concrete seven times less than cement paste (Fig. 3.22).

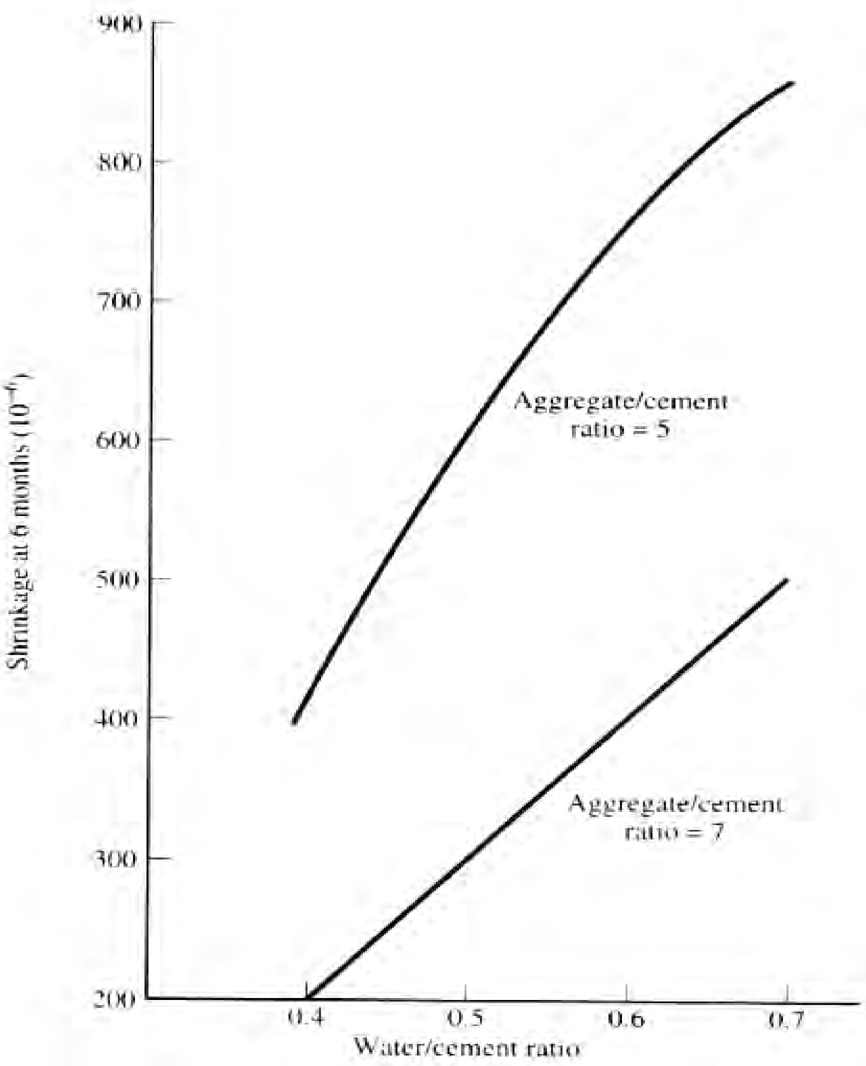


Figure 3.22 Typical variation of shrinkage in concrete specimens.

Shrinkage can be minimized by keeping the water per unit volume of concrete as low as possible (or by keeping the aggregate content as high as possible). Curing lowers the shrinkage. High-pressure steam-cured samples are found to shrink less than normally cured samples. The use of a water-reducing admixture decreases the amount of shrinkage. Retarding admixtures may give rise to more shrinkage.

As noted earlier, restraint provided by reinforcement decreases shrinkage but induces tensile stresses in concrete, causing it to crack. Thus the amount of shrinkage in reinforced concrete is less than that in plain concrete. Reinforcement is provided in slabs on grade (or ground-supported slabs) to control shrinkage. But it is important to recognize that the reinforcement will not prevent shrinkage cracking; it merely controls the location of cracking resulting from shrinkage and temperature effects. Use of synthetic fibers in concrete (fiber-reinforced concrete) helps to control shrinkage cracks. Oversanded aggregates, which require a high water/cement ratio to obtain satisfactory workability, give rise to cracking. Retaining walls and basement walls may crack vertically because of shrinkage.

Different parts of a structure may shrink differently. Foundations may not shrink because they may not dry out. Walls may shrink because of drying out, and floors may shrink more because of indoor heat. This *differential shrinkage* between various elements in a building may lead to cracking, especially at the junction between various members.

A decrease in temperature also causes contraction in concrete. A drop in temperature of I00°F (37°C) may cause a reduction in length of about½ in. per 100 ft (1.7 cm per 30 m). The net reduction in length of concrete is thus due to shrinkage and reduction in temperature.

Contraction and construction joints. As noted earlier, when concrete shrinks without restraint, no cracks will form. But most structures have restraint to shrinkage from reinforcement, soil, foundations, or other members which will lead to cracking. These shrinkage cracks are generally accommodated in large structures (such as pavements) by forming surface grooves every 10 ft or less, called *contraction joints* (Fig. 3.23). These joints (also called *dummy joints* or *control joints)* are meant to direct cracks to the location of grooves. Without these joints the concrete will crack in a random manner.

Control joints are provided in large structures such as sidewalks, floor slabs, driveways, and walls. They can be made by tooling, forming, scoring, or sawing. Forming can be accomplished by placing wood strips or premolded joint material at the joint location, which acts to separate the element on two sides of the joint. The grooves are formed to a depth of about one-fourth the slab thickness and a minimum of one-fifth the thickness. In reinforced concrete slab construction, half the horizontal bars (alternatively) should be cut at the joints. Control joints in walls may be spaced every 20 ft (6 m).

Construction joints (also called *isolation joints*, *expansion joints*, or *bonded joints)* are joints provided to separate a slab from other parts of a structure (such as beams and columns) so as to prevent the bonding and permit horizontal and vertical movement. These joints (Fig. 3.24) are also used at stopping places (when two successive placements of lifts of concrete meet) when concreting large areas. The joint or filler material may be as small as ¼ in. (6.3 mm) thick. For thin slabs a butt-type construction joint is satisfactory. For

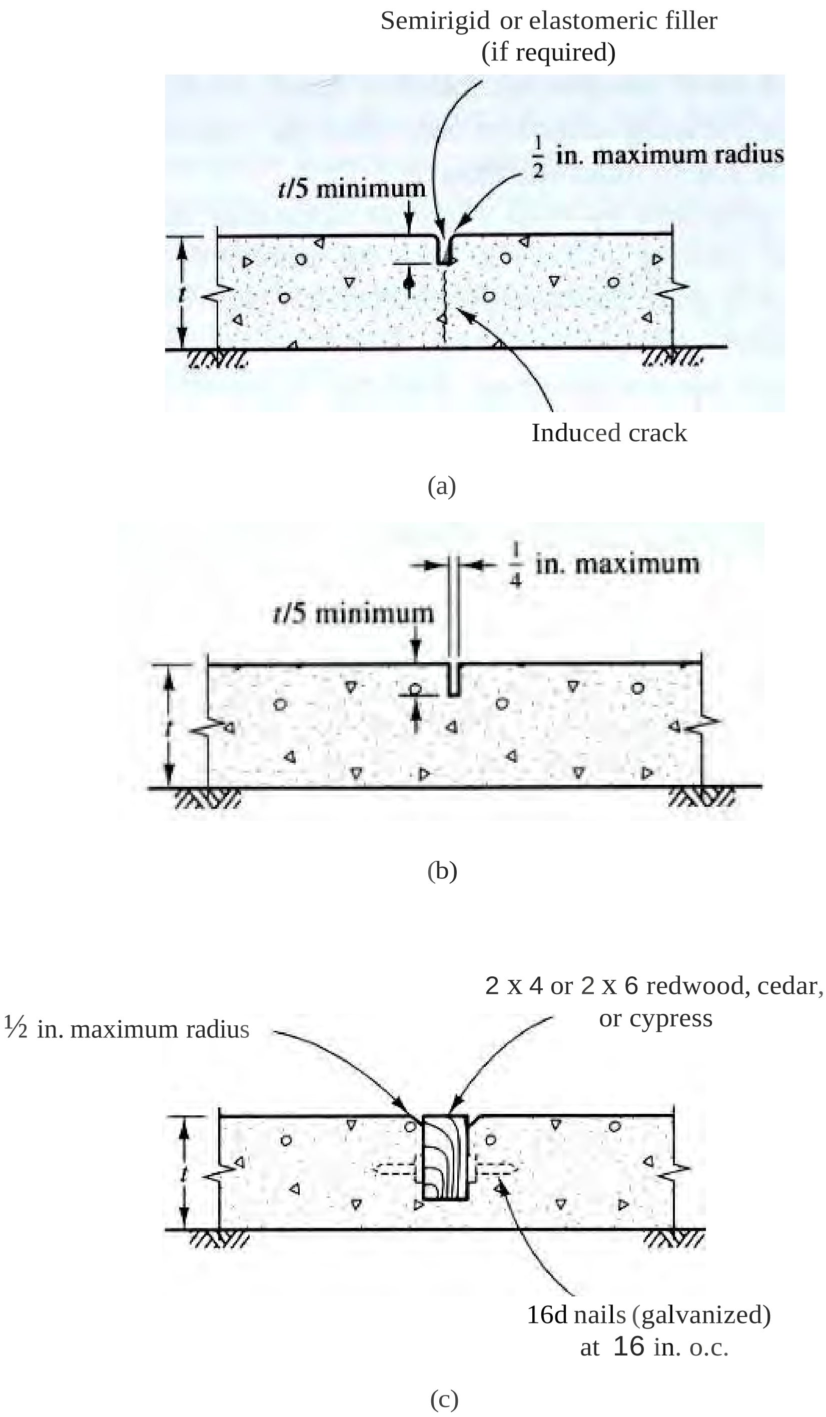


Figure 3.23 Control joints: (a) grooved joint; (b) sawed joint; (c) wood strips.

thicker slabs, a tongue-and-groove joint or doweled butt joint is preferable. When provided around other fixed parts of a building (such as a column), these joints-isolation joints or expansion joints-allow movement between various elements of the building.

3.7.6 Creep

Another important property of hardened concrete is *creep*, which is the increase in strain or deformation with time. When subjected to an external load, concrete deforms elastically, called elastic deformation. But when this loading continues, the deformation increases with time, which is the creep component of net deformation. Thus creep can be defined as the

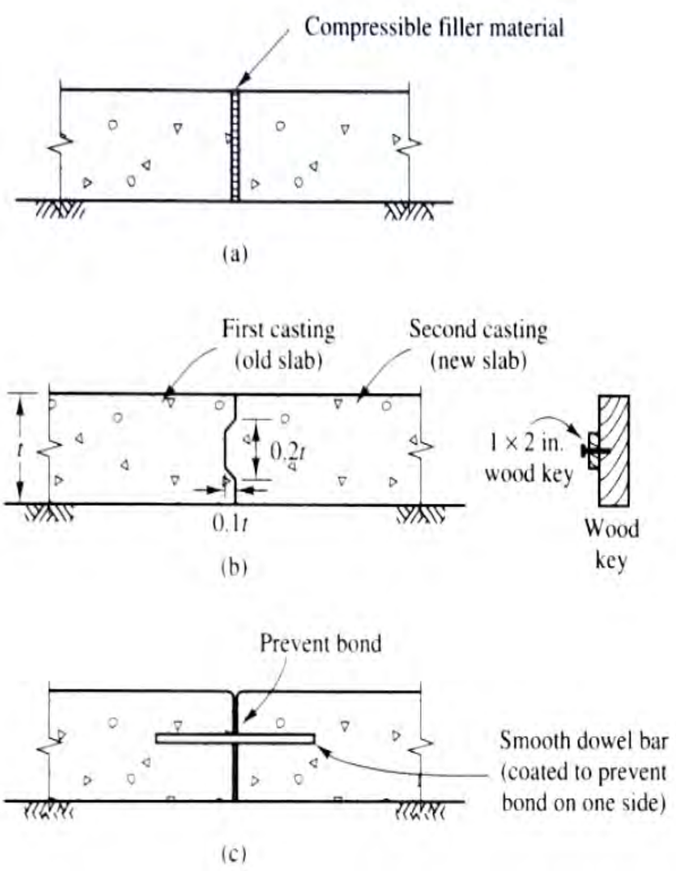


Figure 3.24 Construction joints:
(a) compressible filler; (b) keyed joint.
(c) dowel joint.

time-dependent increase in strain resulting from stresses. This increase can be several times as large as the initial strain or deformation and causes changes in stresses. The common meaning of creep is to sneak up behind someone. In a way, this meaning applies to creep in concrete because it is the component of deformation that follows the elastic deformation.

Generally, aggregates do not creep, and creep in concrete can be attributed to the cement paste. However, aggregate particles restrain creep deformation and result in creep stresses. Concrete made with sandstone and gravel generally creeps more than does that made with granite or limestone. The higher the modulus of elasticity of aggregates, the greater is the restraint offered to the creep movement. The higher the content of aggregates, for a given water/cement ratio, the lower is the creep. The creep of lightweight concrete is about the same as that of normal-weight concrete of similar mix proportions. Typically, creep increases with increase in the water/cement ratio.

Creep occurs under all types of loading: compression, tension, or torsion. It appears rapidly following loading. About 50% of 1-year creep occurs within 3 to 4 weeks after loading. The rate of creep increases with ambient temperature. The earlier the age of concrete at which loading is applied, the greater is the creep. It is higher in a wet than in a dry condition.

Creep deformation is proportional to the applied stress level. It is made up of two components:

- Reversible creep
- Irreversible creep

Upon unloading, there is an immediate recovery (elastic) followed by a delayed recovery, leaving a part of deformation as permanent. The part of creep deformation that can be recovered is the *reversible creep* and the part that has become permanent is the *irreversible creep.*

Creep can also be thought of as a reduction in stress due to external loading. Note that concrete members held at constant length show an increase in tensile stress due to shrinkage and a reduction (in tensile stress) due to creep. If concrete under load is drying, creep and shrinkage deformations are additive. The net increase in strain in such a member is due to shrinkage and creep strains. But it should be noted that creep and shrinkage occur simultaneously, and separation of the two as independent components is for practical simplicity only.

3.7.7 Carbonation

Carbonation is the term used to explain the reaction between concrete and carbon dioxide from the air (which is heavier than air and concentrates on the surface) to create calcium carbonates. This chemical reaction reduces the concrete quality and the ability of concrete to protect reinforcement from corrosion and results in additional shrinkage (in the carbonated region). Resistance to carbonation can be improved by using good-quality dense concrete.

Carbonation starts at the surface and slowly penetrates the concrete. Poor-quality concrete suffers carbonation earlier and deeper. Carbonation causes no serious problem but results in a soft surface, dusting, and color change. But if the surface is subjected to salt, or in a salty environment, carbonation may enhance the reinforcement corrosion.

3.7.8 Durability

Concrete can deteriorate primarily for three causes:

- Alkali-aggregate reaction
- Freeze-thaw cycle
- Sulfate attack

All three factors may occur simultaneously in a concrete structure, leading to expansion and development of cracks. Concrete is said to be *durable* if it can withstand the deteriorating effects of these and other factors.

Freeze-thaw is the process by which water that is stored in voids in concrete expands as a result of freezing temperature. Consequently, the concrete cracks and deteriorates. Entrained air and a low water/cement ratio will improve the freeze-thaw resistance of concrete.

Sulfates in the soil and seawater (primarily, sodium sulfate and calcium sulfate) react with aluminates in cement to produce compounds that have greater volume. This process-called *sulfate attack-causes* expansion and cracking in concrete. Sulfate attack can be minimized by using cement that is low in tricalcium aluminate (type V cement). Fly ash and other mineral admixtures can react with lime-liberated during hydration-and reduce the amount of calcium aluminate. Consequently, the sulfate attack is reduced.

Certain natural aggregates react chemically with alkalis of portland cement (released during hydration) in the presence of water. This is followed by expansion or swelling of the aggregates, resulting in cracking and disintegration of concrete, which is called *alkali-aggregate reaction* or *alkali-silica reaction.* It is a chemical reaction between the siliceous compounds of the aggregates (reactive silica) and alkalis of the concrete. Aggregates that contain silica in its active state (called *reactive aggregates),* such as cherts, siliceous limestones, and certain volcanic rock, exhibit this property.

The alkali-aggregate reaction results in expansion of aggregate particles and eventual cracking of concrete. The cracking-called *map cracking-happens* in horizontal surfaces and as horizontal cracking in walls and beams. The alkalis responsible for this reaction are sodium oxide and potassium oxide. Chemical analysis of the reaction products (whitish amorphous deposits) show them to be composed primarily of sodium and potassium silicates. Note that alkali-silica reaction will not occur if any one of three factors-available alkalis, reactive silica, and moisture-is not present.

The most direct solution to the problem is the use of low-alkali cement any time that aggregates are suspected of containing reactive silica. Use of fly ash or ground blast furnace slag (mineral admixtures) can minimize the alkali aggregate reaction.

In summary, permeability and ultimate compressive strength are the key factors affecting durability. Low strength and high permeability decrease the durability. Well-graded mixture performs better than does poorly graded mixture. Long-term strength (strength gain beyond 28 days) is also important for better durability. When fly ash is used in cement, the reaction between silica in fly ash and lime in hydrated cement produces compounds that fill void spaces in concrete and thus contribute directly to lowering the permeability. Thus fly ash and other mineral admixtures can be used to control sulfate attack and alkali-aggregate reaction and to improve durability.

3.8 MIX DESIGN

The objective of the mix design is to determine the proportions of ingredients to produce concrete that is durable and of required strength properties at minimum cost. The cost of concrete depends on cost of materials, cost of transportation, and labor cost for placing and finishing. in addition, cost of inspection and future repair also contribute to the overall cost. Cement is the costliest ingredient in the mixture, and the lower the cement content, the lesser the cost. As explained earlier, durability and strength depend on a number of factors. In general, strength and watertightness increase with cement content, density of mix, and curing time, and decrease with amount of water. Air-entrained concrete has more resistance than normal-weight concrete.

Generally, the selection of ingredients is based on the following principles:

- The mix is workable.
- Use as little cement as possible.
- Use as little water as possible.
- Gravel and sand should be proportioned to achieve a dense mix.
- The maximum aggregate size should be as large as possible.
- The water/cement ratio determines the strength of concrete.

In most structures the mix design calculations are done by knowing the required compressive strength of concrete. However, when concrete strength is not specified (as in residential foundations, pavements, walkways, etc.), the proportioning is based on an arbitrary selection of materials-primarily the amount of cement. The ingredients are chosen from experience and knowledge of general specifications. In most common forms of construction only the cement quantity is varied between different projects. The amount of water is controlled by workability requirements.

When the compressive strength is specified, the proportioning is generally done using a mix design procedure that is based on workability requirements, void content, and the relationship between strength and water/cement ratio. This mix, called a *trial mix,* is then tested in a lab to determine its compressive strength. If the average experimental strength is different from the expected or required strength, the mix proportions are adjusted accordingly.

The mix proportions thus obtained (called a *dry mix)* should be adjusted based on the moisture content and the absorption capacity of the aggregates. Wet sand has approximately 5 to 10% moisture, and most sand has about 3% moisture. Most gravel and crushed stone have about 2% moisture. The average absorption capacity of sand is about 2% and that of gravel or crushed stone is about 1%. Porous sandstone and lightweight aggregates may absorb a lot of moisture-about 7% and higher. Actual moisture content and absorption capacity of aggregates can be determined using laboratory tests. The final adjusted mix proportions is called the *field mix.*

The trial mix design procedure is formulated to achieve a mix that will satisfy the strength, durability, and workability requirements of concrete as closely as possible. The procedure can be summarized as follows:

1. The water/cement ratio is selected to satisfy strength and durability.
2. Workability (slump) is determined for the type of work.
3. The maximum aggregate size is chosen based on the requirements of the job.
4. Air content is determined from durability requirements.
5. The amount of water and coarse aggregate is chosen based on workability requirements.

Note that all concretes contain some entrapped air, usually between 0.5 and 2%. These air bubbles, which are not evenly distributed in concrete, are relatively large and thus do not affect the workability and durability of the mix. On the other hand, an air-entraining admixture when added to the concrete mixture results in very tiny air bubbles which are distributed evenly with the volume of concrete. This increases the workability of plastic mix and improves the durability of hardened concrete. Thus concretes that are exposed to freeze-thaw cycles should be prepared with air-entraining admixtures which increase the amount of air (called *entrained air)*.

It was pointed out earlier that the stronger concrete is not always the better concrete. An excessively high average strength achieved through unnecessary extra cement can increase cracking and internal stresses. Addition of some admixtures, such as some pozzolans, may reduce the temperature of the interior concrete because of comparatively Little heat generation. The following is a summary of out earlier discussion on strength and workability of concrete.

The water/cement ratio is normally selected based on the required compressive strength. However, the French scientist R. Ferret concluded that the strength of concrete depends on the ratio of absolute cement volume to the space available to it. The higher the cement content, the greater the strength. An increase in the maximum size of aggregates *per se* lowers the compressive strength. The economical water/cement ratio is related to the maximum size of aggregates. As the aggregate size (maximum) increases, the amount of water required to achieve certain workability decreases. Angular aggregates demand more water than do rounded aggregates. The workability of concrete is also affected by the temperature. As the temperature increases, the water required to obtain a desired slump increases. About 2 lb of water is required (per cubic yard of concrete) for every 3°F increase in temperature. Curing is essential for strength development.

3.8.1 Mix Design Procedure

The mix design procedure is given below. Note that the process results in a trial mix, which may need appropriate modifications depending on the test results.

Step 1: Select the slump.

If slump is not specified, a value appropriate for the work can be selected from Table 3.3.

Step 2: Select the maximum aggregate size.

Choose the maximum possible size. The larger the maximum size of well-graded aggregate, the smaller is the total void space. Such a mix requires less mortar per unit volume of concrete. Generally,

$$\textbf{maximum size} \qquad \frac{\textbf{narrowest dimension}}{5}$$

Also,

$$\text{maximum size} \qquad \frac{\text{depth of slab}}{3}$$

$$0.75\ (\text{clear spacing between individual bars or wires})$$

Step 3: Estimate the mixing water and air content.

Table 3.4 provides an estimate of mixing water for a given slump and type of concrete. Air-entrained concrete should be used when concrete is exposed and is required to possess adequate resistance to stresses resulting from temperature fluctuations. The amount of water required (for a given slump) decreases with increase in the maximum size of aggregate. The table also shows an approximate amount of air that can be expected in a well-compacted concrete.

Note that Table 3.5 provides the recommended air content for normal- and lightweight concrete in moderate and severe exposure conditions. A *"moderate exposure"* is one where, in a cold climate, the concrete will be exposed only occasionally to moisture prior to freezing, and where no deicing salts are used. (e.g., some exterior walls, beams, girders, and slabs not in direct contact with soil). A *"severe exposure"* is one where, in a cold climate, the concrete may be in continuous contact with moisture prior to freezing, or where deicing salts are used (e.g., bridge decks, pavements, sidewalks, parking garages, water tanks).

TABLE 3.4 APPROXIMATE MIXING WATER AND AIR CONTENT FOR TRIAL BATCHES

Range of Slump•	Approximate mixing water (lb/yd^3 of concrete) for nominal maximum size of CA (in.):							
(in.)	¾	½	¾		I½	2	3	6
				Non-Air-Entrained Concrete				
1-2	350	335	315	300	275	260	240	210
3-4	385	365	340	325	300	285	265	230
6-7	410	385	360	340	315	300	285	
Approximate air content (%)	3	2.5	2	15	1	0.5	0.3	0.2
				Air-Entrained Concrete				
1-2	305	295	280	270	250	240	225	200
3-4	340	325	305	295	275	265	250	220
6-7	365	345	325	310	290	280	270	
Recommended Air content, (%)[b]	4.5-7.5	4.0-7.0	3.5-6.0	3.0-6.0	2.5-5.5	2.0-5.0	1.5-4.5	1.0-4.0

Source: ACI 211.1-91, Table 6.3.3. Reprinted with permission.

•Refer 10 Table 3.3.

[b] Refer to Table 3.5.

TABLE 3.5 TOTAL AIR CONTENT FOR FROST-RESISTANT CONCRETE

Nominal maximum coarse aggregate size (in.)	Air content (%) Severe exposure	Moderate exposure
¾	7½	6
½	7	5½
¾	6	5
1	6	4½
1½	5½	4½
2	5	4
3	4½	3½

Source: ACI 318-89, Table 4.2.1, revised 1992. Reprinted with permission.

Example 3.2:

Slump = 2 in.
Type = non-air-entrained
Maximum size = ¾ in.

From Table 3.4:

$$\text{Mixing water} = 315 \text{ lb/yd}^3 \text{ of concrete}$$

Step 4: Select the water/cement ratio (w/c).

The water/cement ratio (by weight) is selected by strength and durability requirements. When using type I cement, approximate and conservative values can be estimated from Table 3.6. Note that this table shows the maximum permissible water/cement ratios for

TABLE 3.6 MAXIMUM PERMISSIBLE WATER/CEMENTITIOUS MATERIALS RATIOS BY WEIGHT FOR TRIAL BATCHES

Specified compressive strength f'_c (psi)	Absolute water/cementitious materials ratio by weight	
	Non-air-entrained concrete	Air entrained concrete
2500	0.67	0.54
3000	0.58	0.46
3500	0.51	0.40
4000	0.44	0.35
4500	0.38	

Source: ACI 318-89: Table 5.4, revised 1992. Reprinted with permission.

specified compressive strengths. But the *required average strength* should be higher than the specified strength by the margin shown in Table 3.7 and Fig. 3.25.

Example 3.3:

The specified compressive strength of concrete or the design strength is 3000 psi. Find the *wlc* ratio.

Average strength of cylinder tested must be
3000 + 1200 = 4200 psi (Table 3.7)

Maximum water/cement ratio (Table 3.6)
= 0.58 (normal concrete)

This means that if the mix is made using a *w/c* of 0.58, the average strength expected is ;;::: 4200 psi. When durability controls, the water/cement ratio must be selected from Table 3.8.

TABLE 3.7 REQUIRED AVERAGE COMPRESSIVE STRENGTH FOR TRIAL BATCHES

Specified compressive strength, $f'c$ (psi)	Required average compressive strength $f'c$ (psi)
<3000	$f'c$ + 1000
3000-5000	$f'c$ + 1200
>5000	$f'c$ + 1400

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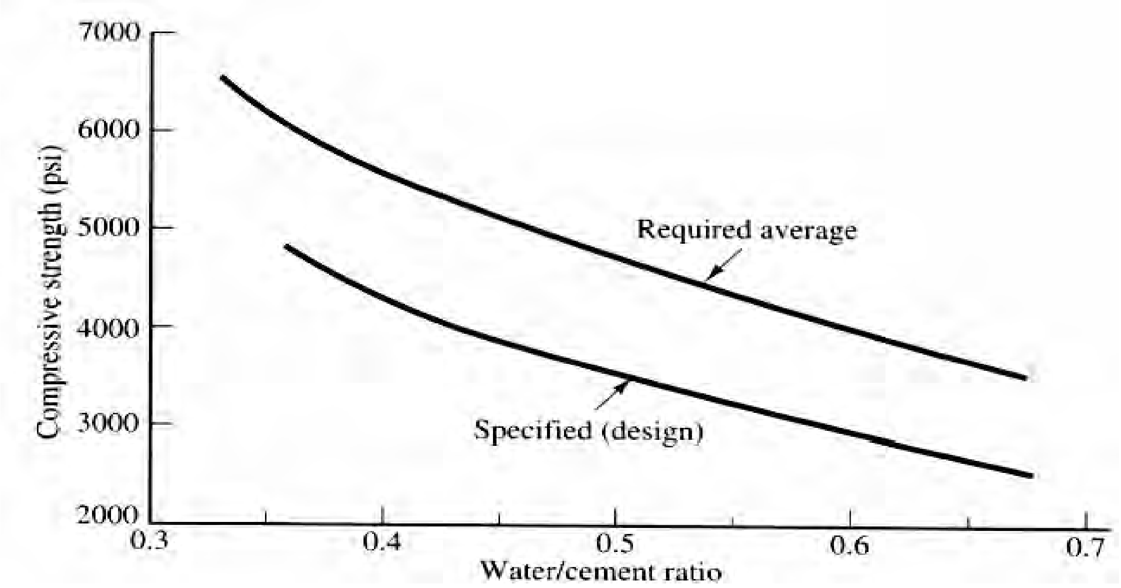


Figure 3.25 Specified and required average strengths.

TABLE 3.8 REQUIREMENTS FOR SPECIAL EXPOSURE CONDITIONS

Exposure condition	Maximum water/cementitious materials ratio, normal-weight aggregate concrete	Minimum f'c normal-weight and lightweight aggregate concrete (psi)
Concrete to have low permeability when exposed to water	0.50	**4000**
Concrete exposed to freezing and thawing in a moist condition	0.45	4500
For protection against corrosion of reinforcement, when concrete is exposed to de-icing salts, brackish water, or seawater	0.40	5000

Source: ACI 318-89, Table 4.2.2, revised 1992. Reprinted with permission.

Example 3.4:

For the concrete for the foundation of a bridge pier, the required average compressive Strength $f'c = 4000$ psi. Find the *w/c* ratio.

The concrete is exposed to freezing and thawing in a moist conditions. Maximum *w/c* ratio= 0.45 (Table 3.8). From Table 3.6, for air-entrained concrete, $w/c = 0.35$, which is less than 0.45. Use a *w/c* ratio of 0.35.

Step 5: Calculate the of cement content.

$$\text{Required cement content, by weight} = \frac{\text{estimated mixing water}}{w/c}$$

Step 6: Estimate the coarse aggregate content.

Table 3.9 gives the volume of coarse aggregate (dry-rodded condition, per unit volume of concrete) to produce concrete of suitable workability. The volume is dependent on the fineness modulus of sand and the maximum size of coarse aggregate.

Example 3.5:

Find the required volume of coarse aggregate to produce a workable mix when

Fineness modulus = 2.6

Maximum size of aggregate = ¾ in.

TABLE 3.9 VOLUME OF COARSE AGGREGATE PER UNIT VOLUME OF CONCRETE BASED ON WORKABILITY REQUIREMENTS

Nominal maximum coarse aggregate size (in.)	Volume of dry-rodded coarse aggregate per unit volume of concrete for fineness modulus of sand:			
	2.4	2.6	2.8	3.0
¾	0.5	0.48	0.46	0.44
½	0.59	0.57	0.55	0.53
¾	0.66	0.64	0.62	0.60
1	0.71	0.69	0.67	0.65
1½	0.75	0.73	0.71	0.69
2	0.78	0.76	0.74	0.72
3	0.82	0.80	0.78	0.76
6	0.87	0.85	0.83	0.81

Source: ACI 211.1-91, Table 6.3.6. Reprinted with permission.

From Table 3.9, the required volume of coarse aggregate per unit volume of concrete= 0.64. For 1 yd^3 of concrete,

dry rodded volume of coarse aggregate = 0.64 (27)

= 17.28 ft^3

Weight of coarse aggregate = (dry-rodded wt) x (dry-rodded density)

For a more workable mix, decrease the amount of coarse aggregate up to 10%.

Step 7: Estimate the fine aggregate content.

All ingredients have been estimated at the end of step 6 except the fine aggregate. The fine aggregate content is determined by calculating the difference between the total volume of concrete and the volume of the remaining ingredients.

Volume of sand = volume of concrete- (volumes of water, cement, coarse aggregate, and air)

$$v_{sand} = V_{conc}\ (V_{cem} + V_{CA} + V_{wat} + V_{air})$$

$$V_S = V_{conc} - (V_C + V_{CA} + V_W + V_@)$$

Volumes of ingredients are calculated by knowing their weights and specific gravities.

Example 3.6:

The amounts of cement, coarse aggregate, and water are as given below. The air content is 2%. The dry-rodded weight of coarse aggregate is 98 pcf. Find the amount of sand.

Water = 340 lb/yd^3 of concrete

Cement = 680 lb/yd^3 of concrete

Volume of gravel = 0.69/unit volume of concrete

Specific gravities of cement, sand, and coarse aggregate are 3.15, 2.65, and 2.68 respectively.

$$V_S = 27 - \left[\frac{680}{3.15(62.4)} + \frac{0.69(27)98}{2.68(62.4)} + \frac{340}{62.4}\right] - \frac{2(27)}{100}$$

$$= 27 - 20.37 = 6.63 \text{ ft}^3$$

$$\text{Weight of sand} = 6.63(2.65)62.4$$

$$= 1096 \text{ lb}$$

Step 8: Find the field mix (based on moisture in sand and coarse aggregate).

Adjust the water content and weights of sand and gravel depending on the moisture contents in sand and gravel. Note that calculations in steps 1 to 7 are based on the assumption that aggregates do not release moisture to or absorb moisture from the mix. In practice, aggregates will contain some moisture, and the weights calculated above have to be increased to compensate for the moisture that is absorbed in and contained on the surface of the particles. In addition, the mixing water amount should be decreased by the amount of free moisture in the aggregates. Free moisture is the difference between the moisture content and the absorption.

Similarly, if the aggregates are dry, they will absorb moisture from the mixing water, and thus the mixing water amount should be increased to compensate for the water absorbed by the aggregates.

Example 3.7:

Find the adjusted amounts for the data shown below.

	Dry weight (lb/yd^3)	Moisture content (%)	Absorption (%)
Cement	580		
Water	320		
Gravel	1940	2	
Sand	1110	6	1.5

$$\text{Required weight of gravel} = 1.02\,(1940)$$

$$= 1979 \text{ lb}$$

$$\text{Required weight of sand} = 1.06(1110)$$

$$= 1177 \text{ lb}$$

$$\text{Required weight of water} = 320 - \frac{(2-1)1940}{100} - \frac{(6-1.5)\,1110}{100}$$

$$= 320 - 19.4 - 50$$

$$= 250.6 \text{ lb}$$

Step 9: Calculate the field mix proportions.

Find the proportions between cement, fine aggregate, coarse aggregate, and water by taking the weight of cement as one unit.

$$\text{Cement:sand:gravel:water} = 1{:}S{:}G{:}W, \text{ by weight}$$

Example 3.8

Use the data in Example 3.7 to calculate the field proportions.

Field mix proportions = 580:1177:1979:250.6

= **I:2.03:3.41:0.43**

Step 10: Calculate the weights of individual ingredients required to make the desired amount of concrete.

The weight of each ingredient is calculated by equating the total volume of individual ingredients to the total volume of concrete.

Example 3.9:

Find the weights using the following data.

Mix proportion = I:2:3.3:0.5

Air content = 3%

Specific gravity of cement, sand, and gravel = 3.15, 2.65, and 2.7, respectively

Required volume of concrete = 2.2 ft^3

Let weight of cement required= *We* lb.

$$\text{Volume of concrete} = 2.2 = \frac{WC}{62.4}\left[\frac{I}{3.15} + \frac{2}{2.65} + \frac{3.3}{2.7} + \frac{0.5}{-1}\right] + \frac{3(2.2)}{100}$$

$$= \underline{6}\overset{\rightharpoonup}{}\underline{4}\,(2.794) + 0.066$$

$$W_C = 481b$$

$$W_S = 48(2) = 96 \text{ lb}$$

$$W_e = 48(3.3) = 158 \text{ lb}$$

$$W_W = 48(0.5) = 24 \text{ lb}$$

3.8.2 Examples of Mix Design

Example 3.10

Determine the field mix proportions using the following data:

Concrete is used for foundation-mild exposure

Specified compressive strength of concrete= 3000 psi

Cement: type I

Maximum size of coarse aggregate = 1½in.

Specific gravity of coarse aggregate= 2.69

Absorption capacity of coarse aggregate= 0.8%

Moisture content of coarse aggregate = 2%

Dry-rodded weight of coarse aggregate= 105 pcf

Specific gravity of fine aggregate = 2.65

Absorption capacity of fine aggregate = 6%

Moisture content of fine aggregate = 8%

Fineness modulus of fine aggregate= 2.6

Solution

Step 1: Select the slump. From Table 3.3, the range of slump for concrete in foundation or footing is I to 3 in. Use a slump of 3 in.

Step 2: Select the maximum aggregate size. Specified (in the data) maximum size is I½in.

Step 3: Estimate the mixing water and air content. From Table 3.5, the range of air content is 4½ to 5½%. Use air-entrained concrete. Assume 5% air. From Table 3.4, the water requirement is 275 lb/yd^3.

Step 4: Select the water/cement ratio. From Table 3.6, for air-entrained concrete of specified compressive strength 3000 psi, water/cement ratio= 0.46.

Step 5: Calculate the cement content. From step 4,

$$\frac{\text{weight of water}}{\text{weight of cement}} = 0.46$$

Thus for **1** yd^3 of concrete,

$$\text{cement required} = \frac{275}{0.46}$$

$$= 5981\text{b}$$

Step 6: Estimate coarse aggregate contents. From Table 3.9, for FM = 2.6,

$$\text{volume of CA} = 0.73 \text{ yd/yd}^3 \text{ of concrete}$$

$$= 0.73(27)105 \text{ lb/yd}^3$$

$$= 2070 \text{ lb/yd}^3$$

Step 7: Estimate the fine aggregate content.

$$\text{Volume of water} = \frac{275}{62.4} = 4.41 \text{ ft3}$$

$$\text{Volume of cement} = \frac{598}{3.15(62.4)} = 3.04 \text{ ft}^3$$

$$\text{Volume of CA} = \frac{2070}{2.69(62.4)} = 12.33 \text{ ft}^3$$

$$\text{Volume of air} = \frac{5(27)}{100} = 1.35 \text{ ft}^3$$

$$\text{Total solid volume except FA} = 4.41 + 3.04 + 12.33 + 1.35$$

$$= 21.13 \text{ ft}^3$$

$$\text{Sand volume required} = 27 - 21.13 = 5.87 \text{ ft}^3$$

$$\text{Weight of sand} = 5.87(2.65)62.4$$

$$= 971 \text{ lb/yd}^3 \text{ of concrete}$$

Dry weight of materials for 1 yd^3 of concrete:

Cement = 598 lb
Fine aggregate = 971 lb
Coarse aggregate = 2070 lb
Water = 275 lb

Step 8: Find the field mix.

Moisture content of CA = 2%
Required weight of CA (moist condition) = 1.02(2070)
= 2111 lb
Moisture content of FA = 8%
Required weight of FA (moist condition) = 1.08(971)
= 1049 lb
Absorption capacity of CA = 0.8%
Free moisture in CA = 2 - 0.8 = 1.2%
Absorption capacity of FA = 6%
Free moisture in FA = 8 - 6 = 2%

$$\text{Net reduction in water} = \frac{1.2(2070)}{100} + \frac{2(971)}{100}$$

= 44.3 lb
Net mixing water required = 275 - 44.3
= 230.7 lb

Step 9: Calculate the field mix proportions. Field mix quantities:

Cement = 598 lb
FA = 1049 lb
CA = 2111 lb
Water = 230.7 lb

Field mix proportions:

cement: FA: CA: water = I:1.75:3.53:0.39

Example 3.11

Find the weight of all ingredients for 1.8 ft^3 of concrete using the field mix proportions from Example 3.10. Specific gravities of FA and CA are 2.6 and 2.7. respectively. The air content is 5%.

Solution From Example 3.10 field mix proportions:

$$\text{cement: FA: CA: water} = 1:1.75:3.53:0.39$$

Volume of concrete, V_{con} is 1.8 ft^3.

$$\begin{aligned} V_{con} &= \frac{W_c}{62.4}\left(\frac{1}{3.15}+\frac{1.75}{2.6}+\frac{3.53}{2.7}+\frac{0.39}{1}\right)+0.05(1.8) \\ &= 1.8\ \text{ft}^3 \end{aligned}$$

Therefore.,

$$\begin{aligned} \text{Weight of cement, } W_c &= 39.7\ \text{lb} \\ \text{Weight of FA} = 1.75\,(39.7) &= 69.5\ \text{lb} \\ \text{Weight of CA} = 3.53\,(39.7) &= 140.1\ \text{lb} \\ \text{Weight of water} = 0.39\,(39.7) &= 15.5\ \text{lb} \end{aligned}$$

3.9 ADMIXTURES

An *admixture* is a material, added to plastic concrete or mortar, other than water, aggregates, cement, and fiber, to change one or more properties of fresh or hardened concrete. It is introduced into the mixture immediately before or after the mixing. A number of different types of admixtures are available in the market that perform one or more functions, such as increasing the plasticity of the mixture, accelerating the strength development, and reducing the heat of hydration.

Some of the admixtures are added to change the properties of fresh concrete, whereas others change the properties of both fresh and hardened concrete. Generally. use of an admixture should be considered where the desired modification (of properties of fresh or hardened concrete) cannot be achieved by changes in the composition of mix proportions.

The admixtures are generally divided into two groups:

- Chemical admixtures
- Mineral admixtures

Natural pozzolanic materials and industrial by-products (or waste products) such as fly ash and slag are common *mineral admixtures. Chemical admixture*, on the other hand, refers to any number of chemicals available in the market, added in very small quantities to the mixture to develop special properties in fresh or hardened concrete. The effectiveness of an admixture in modifying the properties of concrete depends on many factors, such as mix proportions, type and size of aggregates, ambient temperature, type, brand and amount of admixture, and type of cement.

3.9.1 Chemical Admixtures

A number of chemical admixtures are available in the market, sold under different product names, which have been employed successfully to modify the properties of concrete. ASTM identifies a number of types of chemical admixtures, listed in Table 3.10. A brief description of these is given below.

Accelerating admixture. An accelerating admixture (ASTM type C) is added to cement or mortar mixture to accelerate the setting and early strength development of concrete, particularly in cold weather applications. Calcium chloride ($CaCl_2$) the most widely used accelerator, can be used to expedite the concreting operations and to permit early removal of forms and opening of the project for service.

The compressive strength of concrete made with the accelerating admixture, at the end of 3 days, is at least 25% higher than that of concrete without the admixture. It should be noted that early strength development can also be achieved by other means, such as the use of type ill cement, the use of a low water/cement ratio, an increase in cement content, and steam curing. Heating the mixing water and aggregate is one more procedure used to increase the rate of hydration in cold weather.

Calcium chloride is added in solution form as part of the mixing water. The amount of this admixture should be limited to 2% by weight of cement, as a large dose may cause severe corrosion and loss of strength at later ages. This admixture is not recommended in hot weather applications and for prestressed concrete, and may be ineffective at temperatures below freezing because concrete can freeze before it reaches the initial set. Note that accelerating admixture will speed up the early strength gain but does not prevent concrete from freezing. Calcium nitrite, which is a corrosion inhibitor, is also used as an accelerator.

A number of problems are known to follow use of an accelerator. It increases the heat of hydration, and is found to aggravate corrosion of reinforcing and prestressing steel. In addition, shrinkage and creep are found to increase with the addition of calcium chloride as an accelerator.

Retarding admixture. A retarding admixture (ASTM type B) is added to concrete to delay its setting and hardening, especially in hot weather applications [ambient temperature higher than 90° F (32° C)]. High temperature increases the rate of hardening, which makes it difficult to place and finish the plastic concrete. The use of this admixture is also recommended in large structures and difficult situations, such as large piers and foundations, to delay the initial set as well as to keep the concrete workable throughout the entire placing period.

The chemical composition of a retarder is similar to that of a water-reducing admixture, and many products available in the market exhibit both retarding and water-reducing characteristics. Use of this admixture, in general, may reduce the strength of concrete at the early age.

Antifreeze admixture. More than 50% of the United States is hit by freezing temperatures at least one month each year. When fresh concrete is exposed to freezing

TABLE 3.10 CHEMICAL ADMIXTURE

Type	Description	ASTM standards	Applications
A	Water-reducing admixture	C494	To get dense concrete, 1.0 improve workability
B	Retarding admixture	C494	To delay setting and hardening; hot weather concreting; large structures
C	Accelerating admixture	C494	To accelerate setting and early strength development; cold weather concreting
D	Water-reducing and retarding admixture	C494	Similar for types A and 8
E	Water-reducing and accelerating admixture	C494	Similar for types A and C
F	Water-reducing, high-range admixture	C494	In high-strength concrete; to improve watertightness and workability
G	Water-reducing, high-range, and retarding admixture	C494	Similar for types 8 and F
	Air-entraining admixture	C260	To improve durability and workability
	Antifreeze admixture		Cold weather concreting; to minimize freezing of water in fresh concrete

temperatures, strength development is delayed and concrete may suffer from damage due to freezing.

An alternative to protecting the fresh concrete from frost damage (using insulation or by providing heated enclosures) is to use an antifreeze admixture that lowers the freezing point of the pore water in concrete. It may also allow the cement to hydrate at low temperatures. It should be recognized that an antifreeze admixture is used to minimize, not prevent, ice formation in concrete. The long-term effects of this type of admixture on durability and other characteristics of concrete have not been studied. An antifreeze admixture is essentially useful for thin structural elements, as they can lose heat more rapidly.

Water-reducing and high-range water-reducing admixtures. These types of admixtures (ASTM types A and F) are used to reduce the quantity of mixing water required, which increases the compressive strength, and to produce concrete of desired consistency or high slump. A high-range water-reducing admixture is a water-reducing admixture that reduces the water required by 12% or greater.

Sugar in any form is a water-reducing admixture (and a retarder). Its effect is due to increased dispersion of cement particles, causing a reduction in the viscosity of the concrete. But sugar is not used in present-day concrete construction, as it is difficult to control the water-reducing effect and setting characteristics. Moreover, even a moderate amount of sugar slows down or completely stops the setting of cement. A number of admixtures based on lignosulfonates (a by-product of wood industry) are marketed as water reducers and retarders.

The water-reducing admixtures are added, typically, to improve the consistency or workability of concrete, to increase the strength, and/or to attain savings in cement without compromising strength or consistency. Note that consistency or workability can also be improved by other means, such as addition of more cement and water and proper proportioning.

High-range water reducer, also called *superplasticizer,* is added in small dosages with mixing water (typical dosage is 0.2% by weight of cement) to yield a substantial increase in slump (called flowing concrete). Concrete with slumps greater than 7½ in. is called *flowing concrete.* The superplasticizer can be added at the job site or at the batch plant. Dosage rates vary from brand to brand for different types of cement. Additional dosages may be used when the slump has to be maintained.

With the help of superplasticizer it is possible to work with concrete of low water/cement ratios (typically, in the range 0.3 to 0.45), which would be impossible otherwise. Note that at very low water/cement ratios, even a small deviation, as little as 0.01, may have a significant effect on the compressive strength. A low water/cement ratio yields concrete with very high compressive strength (called *high-strength concrete),* generally in excess of 8000 psi.

In addition to the increase in strength, the superplasticizer eliminates segregation and allows good dispersion of cement particles in water. The uniform distribution of cement particles accelerates the rate of hydration and is partly responsible for higher compressive strength at an early age. The general nature of the effects of superplasticizer is explained below.

Mixtures that have a low water/cement ratio are often difficult to place and difficult to work with. As they are stiff, theses concretes demand a lot of labor to place and finish. Any additional water lo the stiff mixture is accompanied by loss of strength and more shrinkage cracks. In addition, the concrete is more apt to have a powdery surface, and be prone to spalling and flaking. The addition of superplasticizer (without increasing the water content), at a cost increase of about 5%, results in a very fluid concrete (slump of 9 to IO in. instead of usual 3 10 5 in.). Labor savings (in the cost of placement and finishing), as a result of superplasticizer, can be as high as 33%.

Concrete made with superplasticizer has a smooth surface, is much less likely to chip and spall, and has fewer plastic shrinkage cracks than does concrete without this additive. Note that plastic shrinkage cracks develop when water evaporates from the plastic concrete, thereby causing a reduction in the volume of concrete. The more water there is in the concrete mix to begin with, the more water that will rise to the top and evaporate and the greater will be the volume reduction of the poured concrete and, therefore, the greater the amount of plastic shrinkage cracking.

In addition to higher compressive strength, low permeability, and less shrinkage, the use of superplasticizer has a number of other advantages, such as less time to place and finish the concrete, an accelerated curing period (because of more rapid gain in strength), and early removal of forms. In fact, the advent of superplasticizer is said to be thesingle most important development in concrete technology in over three decades.

High-strength concrete is being used more and more in columns of high-rise buildings, bridges (to reduce their weights), and offshore structures. Concrete in the lower stories of Chicago's Water Tower Place had a compressive strength of 9000 psi, and the superstructures of the East Huntington Bridge across the Ohio River and the Annicis Bridge near Vancouver, British Columbia, were constructed with 8000-psi concrete. The tallest building in Georgia [842 ft (257 m)]. One Peachtree Center in Atlanta, was recently completed using concrete of strength 12,000 psi in compression. (The mix, with a water/cement ratio of 0.29, had a water-reducing admixture, a retarder, fly ash, and silica fume.)

Air-entraining admixture. Durability of concrete, measured by the number of freeze-thaw cycles that it can withstand without disintegration, is dependent on the amount of entrained air (Fig. 3.26). Air entrainment is a process by which a large number of microscopic air bubbles [diameter ranging from 0.0008 to 0.08 in. (20 to 2000 µm)] are dispersed throughout the concrete. The benefits of this entrained air is that it causes disruption of the continuity of capillary pores (thus reducing the permeability of concrete) and reduces internal stresses caused by expansion of the pore water on freezing.

A number of chemicals called *foaming agents* are marketed which, added in very small amounts (typically about 0.05% by weight of cement) during mixing, can be used to entrain 3 to 10% air. The air-entraining admixture may consist of salts of wood resins, petroleum acids, animal and vegetable fats, and some synthetic detergents (ASTM C260). The amount of air needed to provide adequate freeze-thaw resistance is dependent on the maximum size aggregate and the level of exposure. A I -in. (25 mm) maximum aggregate may require 4.5% air, compared to 6 % air for ¾-in (10 mm) aggregate.

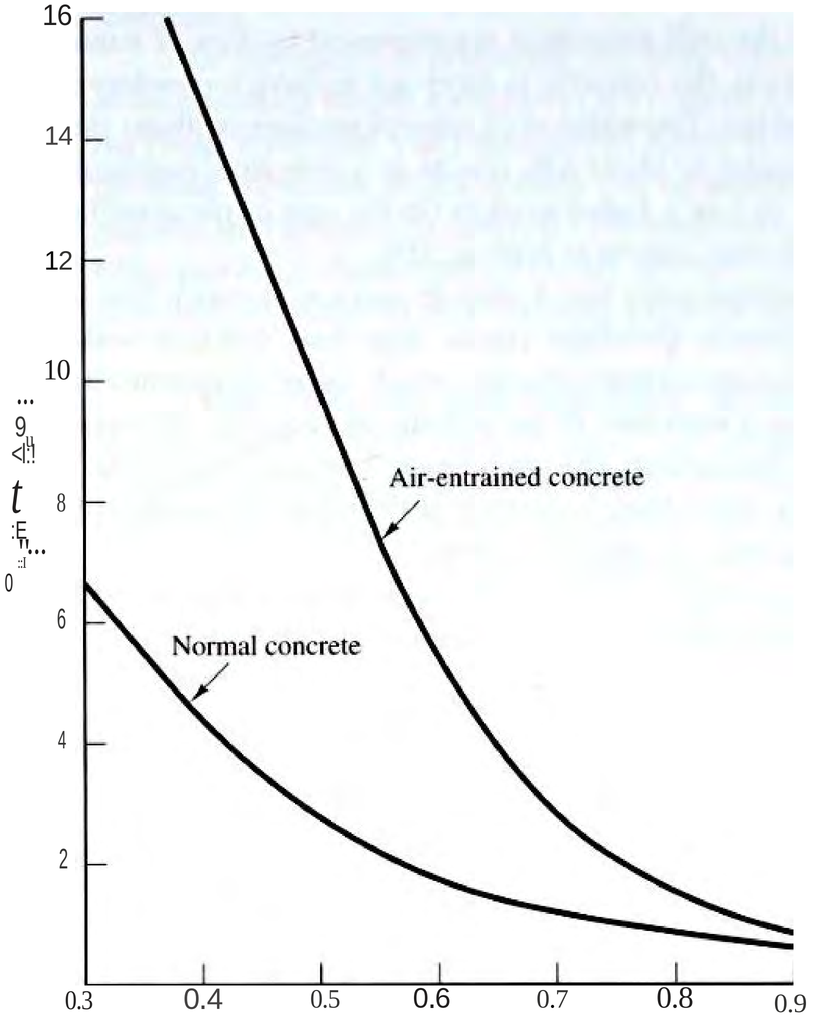


Figure 3.26 Relation between *w/c* ratio and durability factor which is a relative measure of freeze-thaw resistance.

Further advantages of air entrainment are improvement in the workability of concrete (increase in slump) and reduction in bleeding and segregation. The latter decreases the formation of minute cracks below the larger aggregate particles and is thus beneficial from the point of view of permeability. However, air-entrained concrete has compressive strength lower than that of normal concrete of similar cement content and workability by about 10%.

It should be noted that air entrainment can also be accomplished by using air-entrained portland cement (type A cements). But the use of an admixture makes it possible to adjust the quantity of admixture to produce the desired air content.

3.9.2 Mineral Admixtures

Mineral admixtures are natural pozzolanic materials or industrial by products that are used in concrete to replace part of the cement or sand. When added as a substitute for a part of cement, mineral admixtures are called *supplementary cementing material.* The name *pozzolan* comes from the town of Pozzouli, near Naples, Italy, which was a source of volcanic ash. Natural pozzolanic materials were used in construction thousands of years ago. They were used in the construction of the Roman Aqueduct.

Mineral admixtures are generally added in relatively large quantities in comparison with chemical admixtures. Pozzolans include raw and calcined natural materials (class N) such as cherts, shale, tuff, and pumice, and manufactured products (class F or C, ASTM C618) such as fly ash (Table 3.11). Pumice is the most commonly used natural pozzolan.

Pozzolans are siliceous or siliceous and aluminous materials which in themselves possess little or no cementitious property. But in a finely divided form and in the presence of moisture, these materials can react with calcium hydroxide (Lime) of concrete at ordinary temperatures to form compounds of cementitious properties. A brief description of the action of the pozzolan follows.

A by-product of the initial reaction between cement and water is calcium hydroxide. This product contributes very little to the strength of concrete, but it can react slowly with a pozzolanic material such as fly ash. This reaction is called *pozzolanic reaction*. Because the pozzolanic reaction is much slower than the initial cementitious reactions, the strength of concrete made with a pozzolan, at early ages, is lower than that of concrete made without the pozzolan. But the ultimate strength is nearly the same or larger.

However, the benefits of adding pozzolan are in its ability to make concrete that is more durable and less permeable. In addition, the heat of hydration is much lower than that made of normal concrete as well as the shrinkage. Thus pozzolanic cement is ideal for use in hydraulic structures where wet conditions improve the properties of concrete continuously. Also, tests have shown that deleterious expansion of reactive aggregates can be effectively suppressed by using pozzolanic material such as fly ash and slag cement.

Fly ash. *Fly ash* is a by-product of burning powdered coal in electric generating power plants. It is collected in the dust collection systems that remove particles from the exhaust gases. It is generally finer than portland cement and consists mostly of small spheres of glass of complex composition involving silica, ferric oxide, and alumina.

Fly ash has been used in marine structures in the United States since the late 1940s. Presently, there are two major classes of fly ash:

- Class F fly ash
- Class C fly ash

Class F fly ash (low-calcium fly ash) is obtained from burning of bituminous coal, whereas *class* C *fly ash* (high-calcium fly ash) results from burning of subbituminous coal or lignite. The class F fly ash possesses little or no cementitious value. But in a finely divided form and in the presence of water, it will react with calcium hydroxide of cement. The class C fly ash has cementitious properties in addition to pozzolanic properties.

Fly ash is very similar in size, color, and texture to many portland cements. It ranks high in weight of minerals produced yearly in the United States behind stone, sand, gravel, coal, iron ore, or cement. Its properties vary among geographical areas. Most fly ashes are alkaline, a condition that is enhanced by the addition of portland cement.

Fly ash can be used in concrete either as an admixture or as an ingredient in blended cement. Addition of fly ash improves the placement of concrete-its workability and pumpability-because of the fineness of the material and its spherical shape. It helps to lower the heat of hydration (due to slower rate of hydration) and provides a long-term

TABLE 3.11 MINERAL ADMIXTURES

Type/ class	Description	ASTM standard	Applications
N	Raw or calcined natural pozzolan	C618	To improve durability and impermeability; in low-heat applications; in hydraulic structures; to improve sulfate resistance and alkali-aggregate reaction
F	Fly ash, bituminous coal origin	C618	To have high later-age strength; low-heat cement, mass concrete; to improve sulfate resistance and alkali-aggregate reaction
C	Fly ash, lignite ash or subbituminous coal origin	C618	
	Other pozzolanic materials. such as calcined clays and shales and volcanic luffs		
	Silica fume		In high-strength concrete; to improve watertightness; in shotcrete

strength gain for most concretes. Lower heat of hydration is an important property in mass concrete structures such as large foundations, piers, embankments, and bridges. Further, concretes with fly ash show less bleeding than do control mixtures.

The reaction between fly ash and calcium hydroxide (the pozzolanic effect) produces a refined calcium silicate hydrate binder which makes the concrete less permeable (see also Section 3.7.8). Expansion resulting from alkali-aggregate reaction is greatly reduced by incorporating 30 to 40% fly ash (by weight) as partial replacement for portland cement. Fly ash has also been used in concrete susceptible to sulfate attack for more than 50 years. (Cements low in C_3A are more resistant to sulfate attack. Type II cement contains less than 8% and type V cement less than 5% C_3A. Addition of fly ash decreases the total amount of C_3A in the mixture.) Since the cost of fly ash is about one-third that of cement, the concrete made with fly ash is cost-effective.

Summarizing, general benefits of adding fly ash to concrete are:

- increased ultimate strength (later age strength)
- Reduced temperature rise
- Reduced alkali-aggregate reaction
- Improved resistance to sulfate attack
- Reduced permeability
- Improved workability
- Economy

Typically, fly ash is used to substitute about 20% of cement in concrete, although as much as 70% fly ash replacement has been used. About 20 to 25% replacement usually meets normal strength requirements at 28 days. The vast majority of fly ash used in the United States is of class F type.

Problems arising from the addition of fly ash are that it can affect the air content and water demand of the mix. The water demand increases with the fineness; the finer the material, the more air-entraining admixture is required to have the desired air content. The early-age-strength development is slower for high-volume fly ash concrete. As it is darker than normal portland cement, fly ash may affect the color of concrete made with it.

Generally, all pozzolanic materials (natural products or fly ash) may require sufficient moist curing to satisfy durability requirements. Fly ash concrete is found to carbonate faster than concrete without fly ash and is thus more susceptible to corrosion. *Carbonation* (which was explained earlier) refers to the reaction between concrete and carbon dioxide of environment. A decrease in the pH of the concrete, resulting from carbonation, may lead to corrosion of reinforcing bars.

Silica fume. *Silica fume* or *condensed silica fume* (also called fumed silica) is a by-product of the electric arc furnaces in the silicon metal and ferrosilicon alloy industries. At very high temperatures reduction of qua1tz to silicon produces SiO vapors which after oxidation condense to tiny particles (less than 0.1 μm, or about two orders of magnitude finer than cement) consisting of noncrystalline silica (85 to 95% silicon dioxide). Due to its fineness and high glass content, silica fume is a very highly pozzolanic material, and the results of pozzolanic reaction evident at early ages rather than later as with fly ash. Typically, silica fume is added to produce very high strength, dense concrete.

The United States and Norway are the world's largest producers of silica fume, which was first tried as a concrete admixture around the 1950s. Since then it has been used successfully in structural concrete to improve its strength and durability characteristics. An increase in compressive strength of 40 to 60% may be expected due to the addition of about 8 lb (3.6 kg) of silica fume for each sack of cement. Trump Palace in New York City is the first large-scale project in the eastern United States where silica fume was used to obtain high-strength concrete. The reinforced concrete columns in this tower has a specified compressive strength of 12,500 psi (86 **MPa).** Silica fume is presently used to make high-strength concrete for bridge decks, columns, and walls. It is also used in shotcrete application.

Silica fume is commonly available in three forms: water slurry, dry uncompacted powder, and dry densified (compacted) powder. The slurried silica fume contains 50 to 55% by weight of silica fume, the balance being water. Handling the uncompacted powder may pose a health hazard, as the particles are very minute (resembling tobacco smoke) and may end up in the human body.

Addition of silica fume may increase the water requirements in concrete unless a water-reducing admixture is used. Generally, concretes made with silica fume bleed very little. This is because such mixes typically have a low water content, the ingredients tend to stick together, and the silica fume (with a high surface area of particles) renders the mix so impermeable that the limited water available cannot move to the surface. Without bleeding the concrete surface may begin to dry rapidly, which can lead to a weaker surface and more plastic shrinkage cracks. Extra precautions have to be taken to avoid rap.id evaporation of water from the surface. The use of an evaporation retardant or fog spray may help.

Blended hydraulic cement. The ASTM (C595) identifies a special class of cement, called *blended hydraulic cement,* which is made by blending portland cement with either cooled blast furnace slag or pozzolanic material such as tly ash. This specification covers five classes of blended cement: portland-blast furnace slag cement, portland-pozzolan cement, slag cement, pozzolan-modified portland cement, and slag-modified portland cement.

Blast furnace slag is the nonmetallic product, consisting essentially of silicates and aluminates of calcium and other bases, that is developed in a molten condition simultaneously with iron in a blast furnace. Granulated blast furnace slag is the glassy granular material formed when molten blast furnace slag is rapidly chilled as by immersion in water. The resulting product is dried, partially ground, mixed with hydrated lime, and then interground into a very fine powder. This cement, called *slag cement,* is much more plastic than portland cement. It is best suited for foundation structures that are not exposed to weather.

Portland-pozzolan cement, produced by intergrinding portland cement clinkers and natural or artificial pozzolan has better strength characteristics and watertightness than portland cement. Properties of concrete made with blended cement are similar to those made with portland cement plus pozzolan. Effects of various pozzolans on the setting, shrinkage, and other properties have been discussed earlier. Tests have shown that concretes made with silica fume, fly ash, and blast furnace slag blended cements are much better than concrete made with ordinary cement in terms of superior strength, lower permeability, lower heat of hydration, and longer time to initiate corrosion.

3.10 TYPES OF CONCRETE

Ordinary concrete possesses good compressive strength but exhibits weaker characteristics when subjected to tension, flexure, or shear. In addition, concrete suffers from shrinkage, creep, and thermal expansion and contraction, which produce cracks that are detrimental to its performance. For these reasons and to impart ductility to the structure, concrete is very commonly used in combination with materials that possess high tensile or flexural strength. Plain concrete is rarely used for structural purposes. Concrete made ductile through coalition with high-moduli materials is commonly called structural concrete. Some of the more common types of structural concrete are discussed in this section.

3.10.1 Reinforced Concrete

Reinforced concrete is a composite material made by combining concrete and reinforcing steel. Historians consider that *reinforced concrete* originated when Jean-Louis Lambot constructed a reinforced concrete rowboat in 1850. Another Frenchman, François Coignet, is reported to have built a roof of reinforced concrete in 1853, and Joseph Monier, a Parisian gardener, began making flower tubs using a system of reinforcing steel and concrete around the same time.

In principle, reinforced concrete is a system formed by combining two entirely different materials-concrete and steel-so that the system behaves as a unit. Steel *(reinforcing steel),* made up primarily of round bars, is located at all sections where external loads cause tensile stresses. In the history of reinforced concrete various steels were used, ranging from soft steels, with a yield strength of 30 ksi (207 MPa), to hard steels of yield strength of 60 ksi (413 MPa).

Today, reinforcing steel is manufactured to meet the requirements of four **ASTM** standards:

- A615 (deformed and plain billet steel bars)
- A616 (rail steel, deformed and plain bars)
- A617 (axle steel, plain and deformed bars)
- A706 (low-alloy steel bars)

Mechanical properties of these are shown in Table 3.12.

The reinforcing steel is available in different strengths or grades. The term *grade* refers to the specified yield strength. Grade 40 has a specified yield strength of

TABLE 3.12 MECHANICAL PROPERTIES OF ASTM REINFORCING **BARS**

Type of steel and ASTM No.	Identification mark	Size (Nos.) inclusive	Grade (min. yield)	Yield strength (min.) (psi)	Tensile strength (min.) (psi)
Billet steel	S,N	3-6	40	40,000	70,000
A615 - 84a	S,N	3-11 14,18	60	60,000	90,000
		11-18	75	75,000	100,000
Rail steel	I	3-11	50	50,000	80,000
A616-84	R	3-11	60	60,000	90,000
Axle steel	A	3-11	40	40,000	70,000
A617		3-11	60	60,000	90,000
Low-alloy steel A706-84a	W	3-11. 14,18	60	60,000	80,000

40,000 psi (276 MPa), grade 50 has a specified yield strength of 50,000 psi (345 MPa), and grade 60 has a specified yield strength of 60,000 psi (413 MPa). Bars of grade higher than grade 60 are also available but are not commonly used in reinforced concrete. The modulus of elasticity of all grades of steel is taken as 29,000 ksi (200 x 10^3 **MPa).** Plain bars in any grade have a smooth surface, whereas deformed bars are manufactured with surface deformations to achieve perfect bonding with concrete (Fig. 3.27).

The reinforcing bars are available in nominal diameters from ¾ to 1¾ in. *in ¼-in.* increments, and also in two larger sizes: 1¾ in. and 2¼ in. diameter. They are identified

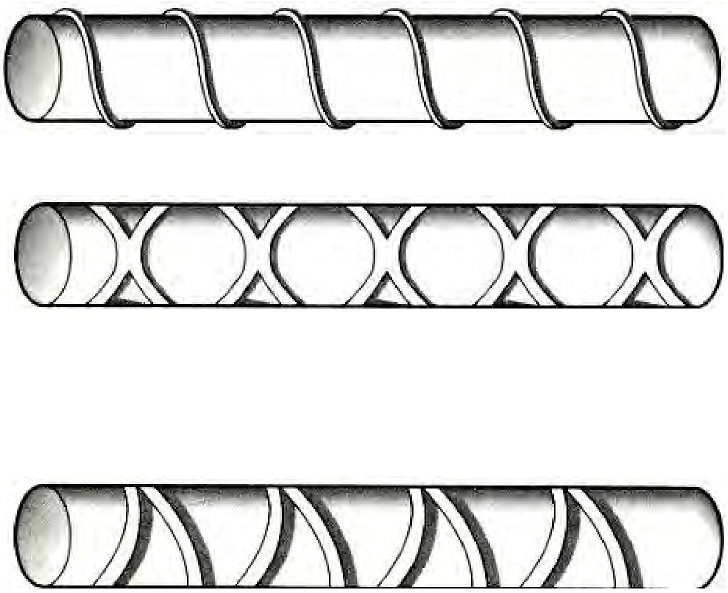


Figure 3.27 Reinforcing bar surface deformations.

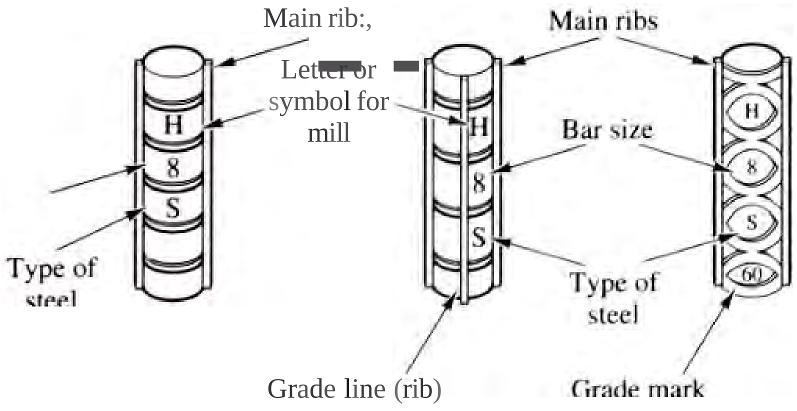
by number; the number corresponds to the number of eighth-inches in the nominal bar diameter. For example, a No. 8 bar has a nominal diameter of I in.; similarly, a No. 3 bar has a nominal diameter of¾in. (Table 3.J 3).

AU reinforcing bars have distinguishing marks that are rolled into the surface of one side of the bar. These markings represent (J) the producer's mill designation or point of origin. (2) the bar number, (3) the type of steel (refer to symbols in Table 3.12), and (4) the number 60 or a single continuous longitudinal line offset from the center of the bar side in the case of grade 60 steel only (Fig. 3.28).

Apart from groups of reinforcing bars, other forms of reinforcing, such as welded wire mesh, are also used in slabs and pavements. The mesh consists of longitudinal and transverse cold-drawn steel wires, placed at right angles and welded at all points of intersection.

TABLE 3.13 SIZE AND AREAS OF STANDARD REINFORCING BARS

Bar size (number)	Nominal diameter (in.)	Nominal area (in^1)	Weight (pcf)
3	0.375	0.11	0.38
4	0.50	0.20	0.67
5	0.625	0.31	1.04
6	0.75	0.44	1.50
7	0.875	0.60	2.04
8	1.0	0.79	2.67
9	1.13	1.0	3.40
10	1.27	1.27	4.30
11	1.41	1.56	5.31
14	1.69	2.25	7.65
18	2.26	4.0	13.60

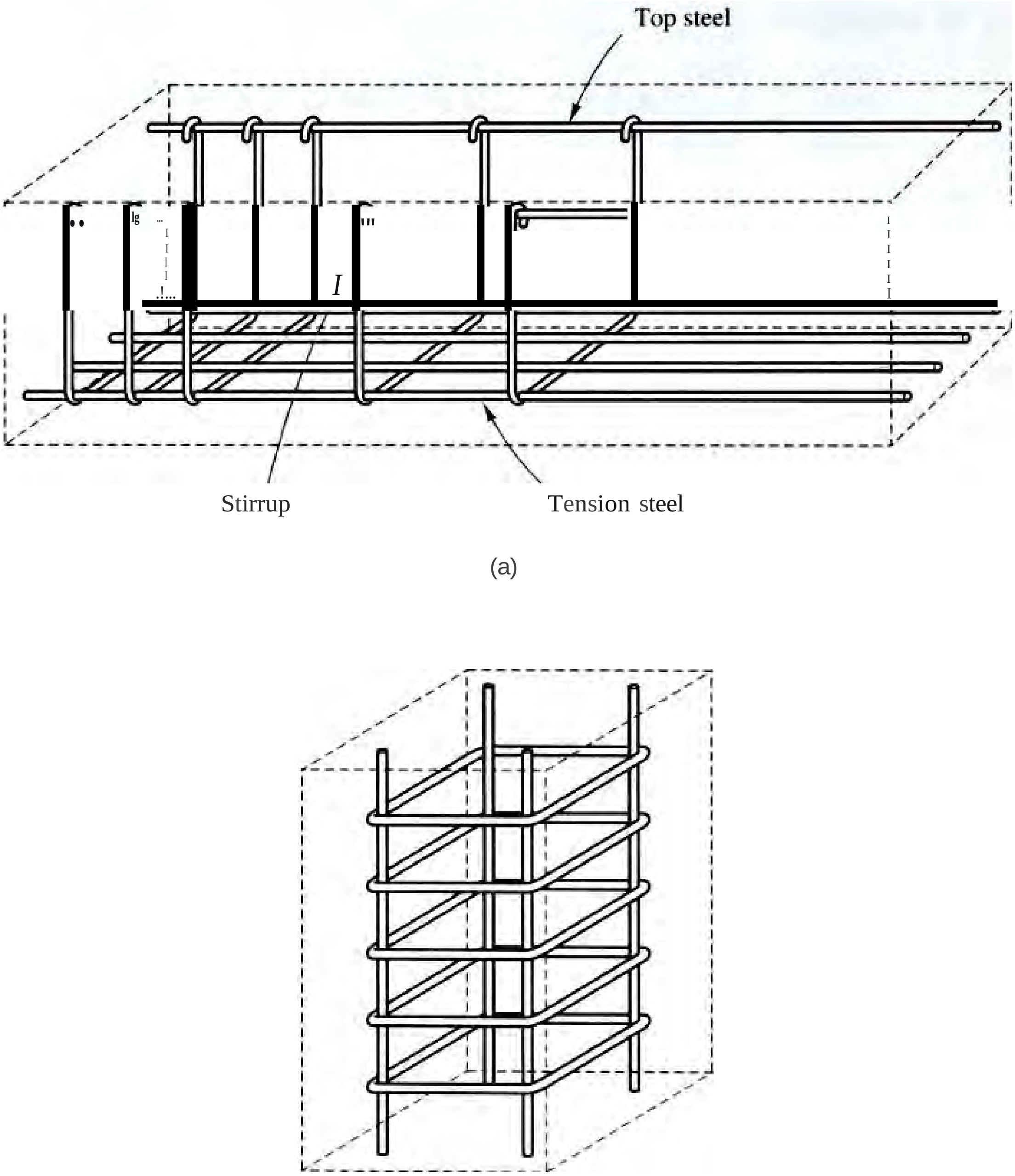


Grade 40 and grade 50

Grade 60 and A706

Figure 3.28 Identification marks on reinforcing bars.

Reinforced concrete construction is typically carried out by forming a cage of reinforcing steel and filling it with concrete. A typical cage is shown in Fig. 3.29 and consists of bars that are parallel to horizontal and vertical planes. For the development of composite action it is essential that all individual bars be bonded to concrete, which means that every bar should have a minimum cover of concrete and the mix should be homogeneous. To accomplish the objective of homogeneity, the consistency of the concrete mixture should be such as to prevent segregation and formation of voids. The proper amount of water, use of admixtures, and adequate vibration generally bring out acceptable results.



(a)

(b)

Figure 3.29 Typical reinforcing cages: (a) beam; (b) column.

Reinforced concrete, the most common material of construction in the world, is used in foundations, breakwaters, high-rise buildings, dams, and residential construction. **With** proper quality control it can be built to withstand all types of weather conditions and loads. It is still the most durable construction material in adverse surroundings such as soil and seawater. Compared to structural steel, reinforced concrete offers a number of advantages, such as reduction in floor vibrations, greater fire protection, and contribution to overall stiffness of the structure.

Moment capacity. The moment capacity of a reinforced concrete flexural member depends on the cross-sectional dimensions, strength of concrete, grade of steel, and area of steel. Increase in any one of these variables increases the moment capacity. When all other variables remain unchanged, moment capacity becomes bigger with increase in steel area.

The failure moment, or *nominal moment capacity* of a reinforced concrete flexural member (beam or slab), M_n an be predicted using the following equation:

$$M_n = A_s f_y (d - 0.5 a)$$

where A_s is the area of cross section of all reinforcing bars on the tension side of the member , f_y the yield strength of steel, d the depth of steel measured from the compression side of the member (called *effective depth),* and a the stress block depth found as below.

$$a = \frac{A_s f_y}{0.85 f_c' \, b}$$

Note that b is the width of member. The theoretical relationship between moment capacity and steel ratio is plotted with some experimental values in Fig. 3.30.

3.10.2 Prestressed and Precast Concrete

The term *prestressing* refers to applying a preload on a structure or structural element before the application of design loads. *Prestressed concrete* is a structural composite material made with ordinary concrete and high-strength steel (prestressing steel) subjected to a pretensile force.

Concrete is essentially a compression material. Its strength in tension is substantially lower than the compressive strength. Provision of reinforcing bars to take up tensile stresses will result in a composite material (reinforced concrete) that has a high flexural capacity but in which the concrete is cracked along the tension zone. These cracks, expected before the application of full service loads. do not ordinarily affect the structural integrity or capacity. However, they make the concrete more permeable and less durable. Application of the prestressing force (by pretensioning the steel or precompression of concrete) accounts for a crack-free concrete that is superior to regular concrete in terms of strength, deflection characteristics, and durability.

Renowned French engineer Eugene Freyssinet is credited with the development of prestressed concrete and the construction of a number of prestressed concrete bridges in France after the 1940s. At present, prestressed concrete is used in various

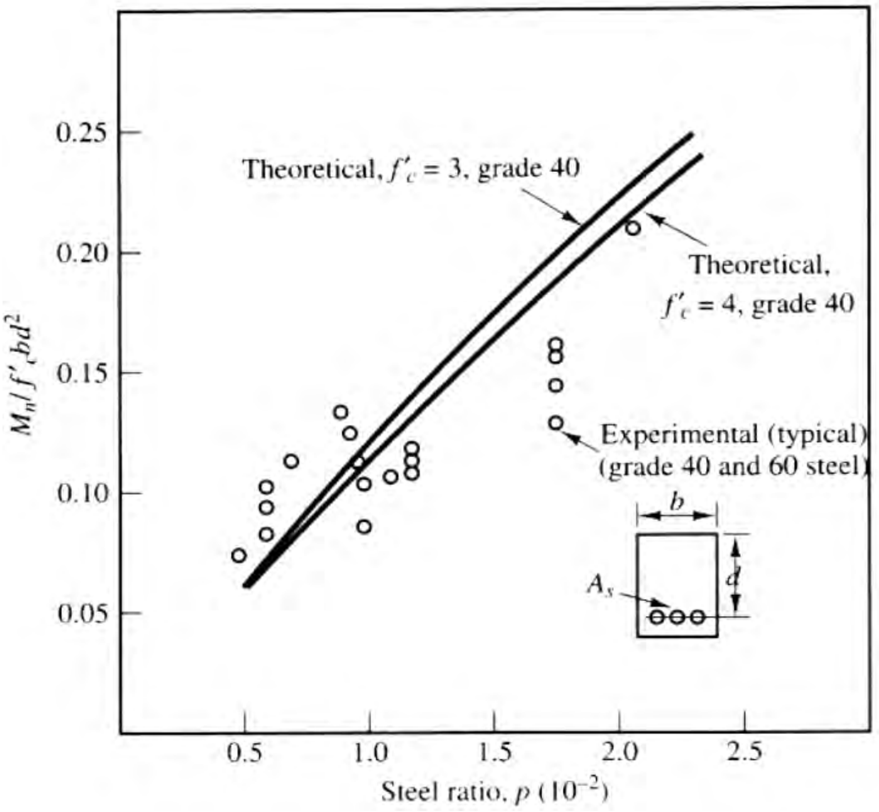


Figure 3.30 Moment capacity of reinforced concrete versus steel ratio.

types of construction, such as bridges, parking garages, foundation slabs, liquid storage tanks, and high-rise buildings.

All prestressed concrete members can be placed in one of two categories:

- Pretensioned concrete
- Posttensioned concrete

Pretensioned prestressed concrete (or pretensioned concrete, Fig. 3.31) members are produced by stretching the prestressing steel between external anchorages before the concrete is placed. As the plastic concrete hardens it bonds with the steel. When the concrete attains the desired strength the jacking force is released, and this force is transmitted by bond from steel to concrete. In the case of *posttensioned prestressed concrete* (or posttensioned concrete), hollow conduits containing unstressed prestressing steel are placed in the forms, to the desired profile, before placing the concrete. When the concrete has gained sufficient strength, the steel is stretched using a jack at one end and by providing special fittings at the other end of the member. When sufficient tension is in the steel, as measured by gauges, the steel is anchored against concrete at the jacking end with special fittings and the jack is removed (Fig. 3.32).

There are three common forms in which steel is used for prestressed concrete:

- Cold-drawn wires
- Stranded cable
- Alloy-steel bars

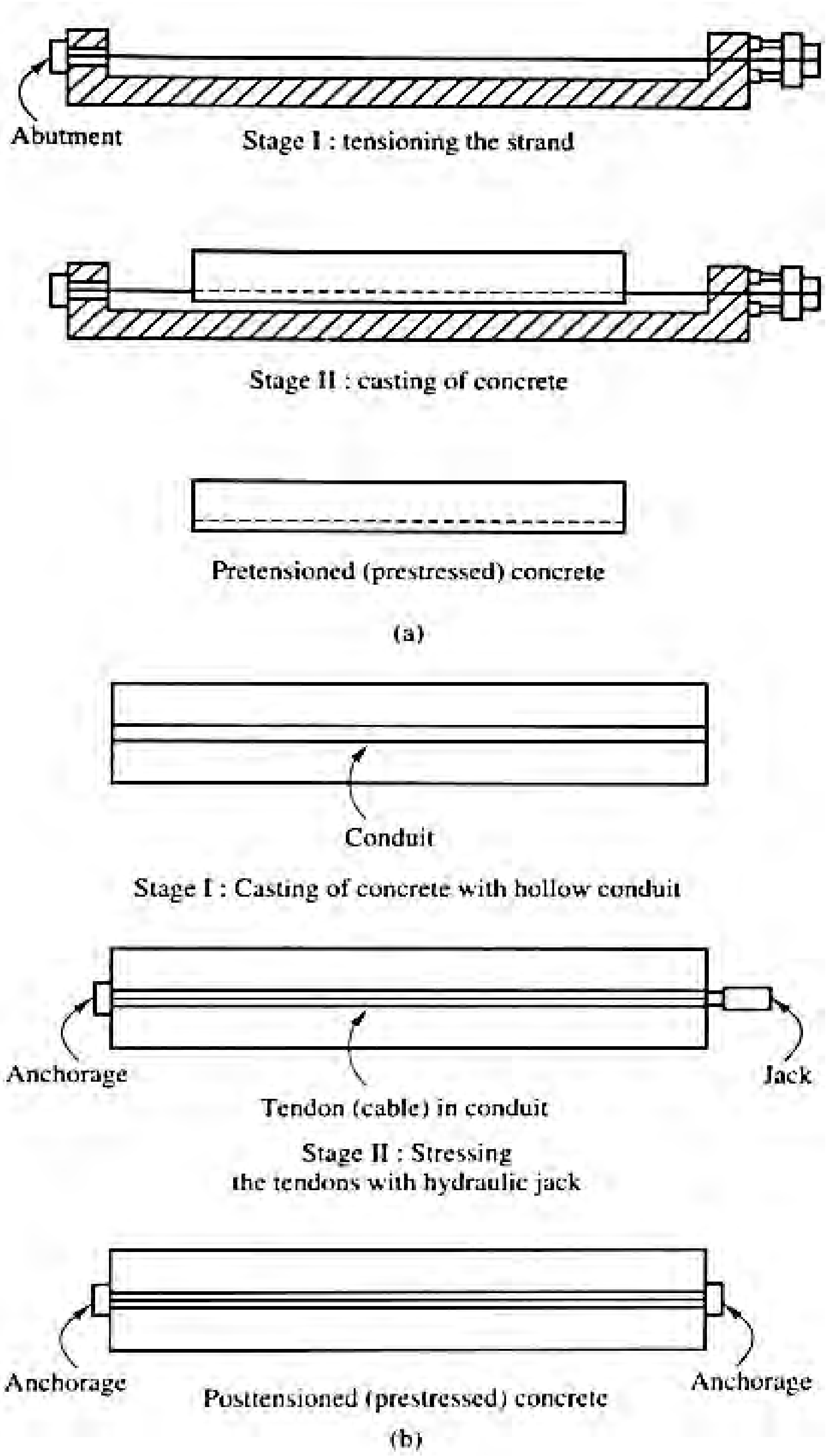

Abutment
Stage I : tensioning the strand
Stage II : casting of concrete
Pretensioned (prestressed) concrete
(a)
Conduit
Stage I : Casting of concrete with hollow conduit
Anchorage
Jack
Tendon (cable) in conduit
Stage II : Stressing
the tendons with hydraulic jack
Anchorage
Anchorage
Posttensioned (prestressed) concrete
(b)

Figure 3.31 Methods of prestressing: (a) pretensioning: (b) posttensioning.

The round wires (ASTM A42 I), available in diameters of 0.192 in. (4.88 mm), 0.196 in. (4.98 mm), 0.25 in. (6.35 mm), and 0.276 in. (7.01 mm). are used for posttensioned construction. Stranded cables (or strands) are almost always used for pretensioned construction and are also often used for posttensioned construction. They are fabricated with six wires wound tightly around a seventh of slightly larger diameter, and are often called uncoated seven-wire stress-relieved strand (ASTM A416). These st

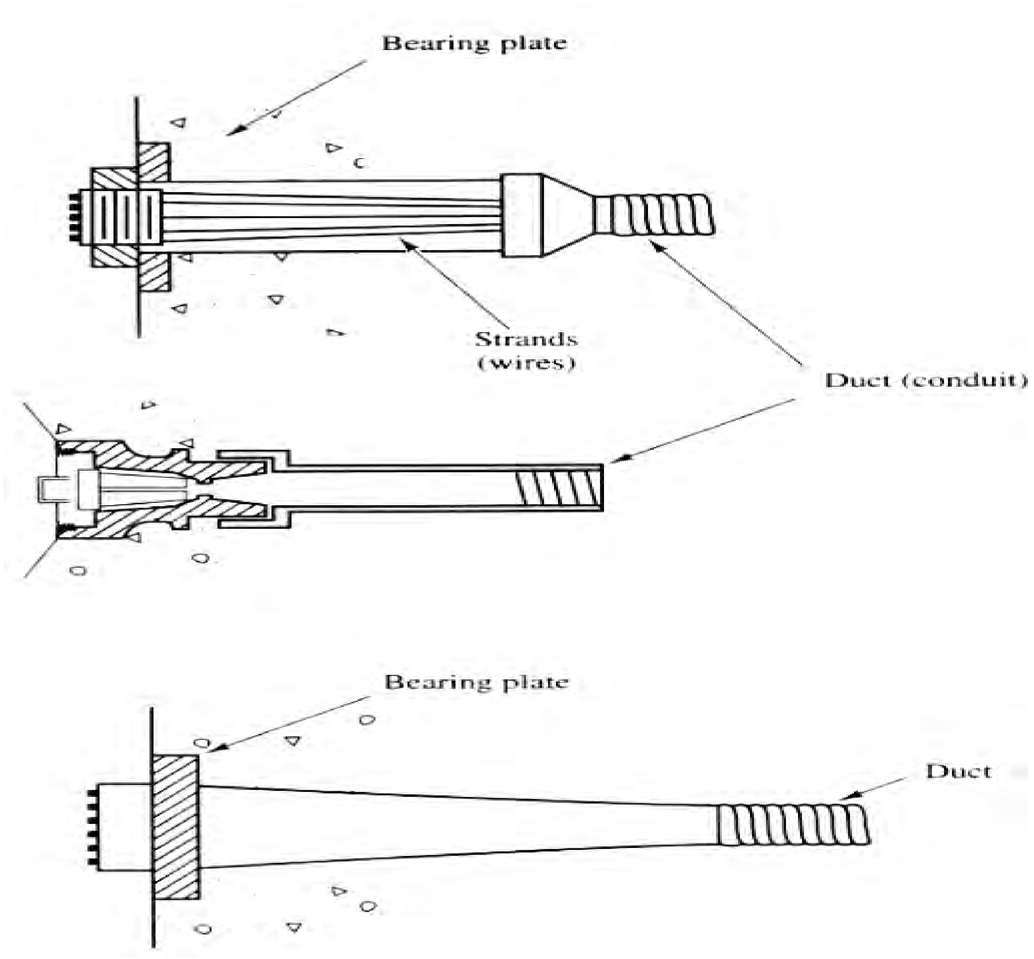


Figure 3.32 Posnensioning anchors.

may be obtained in a range of sizes from 0.25 to 0.60 in. (6.35 to 15.24 mm). Wires and strands can be obtained in tensile strengths ranging from 235,000 to 270,000 psi (1622 to 1860 N/mm^2).

Precast concrete. *Precast concrete* can be defined as concrete that is cast in some location other than its final position in the finished construction. The casting location can be a precast concrete factory or job site. Precast concrete members are reinforced with mild steel reinforcing bars, prestressing steel, or a combination of the two.

Precast concrete is both a construction material and a construction method. High-strength concrete under good quality control is used in its manufacture. As a method of construction, precast concrete can greatly reduce construction time since the elements are cast and stockpiled while other phases of the project are performed. Precast concrete is used in parking garages, buildings, and exterior facades of high-rise structures.

3.10.3 Fiber-Reinforced Concrete

Fiber-reinforced concrete is concrete containing discontinuous discrete fibers. Ordinary concrete contains numerous microcracks, which are responsible for its low tensile strength. Fiber-reinforced concrete offers a solution to this problem of cracking by making concrete tougher and more durable. *Toughness* is defined as the amount of energy needed to produce a specified damaged condition or complete failure of the materials. It measures the ability of the material to support loads even after the formation of cracks. Fiber-reinforced concrete is much tougher and more resistant to impact than plain concrete.

Fiber-reinforced concrete (steel fibers) was developed in the United States in 1969 (J. P. Romauldi and Batelle Development Corp., Cleveland, Ohio). Various kinds of fibers can be used as fiber reinforcement. The most common are steel, polypropylene, nylon, and glass. Typical properties of these fibers are shown in Table 3.14.

Fibers come in various sizes and shapes. Round steel fibers, made from low-carbon steel or stainless steel, have diameters in the range 0.01 to 0.039 in. (0.25 to 1 mm). Flat steel fibers, produced by shearing sheet or flattening round wire, are available in thicknesses ranging from 0.006 to 0.016 in. *Crimped* and *deformed steel fibers* are available both in full length or crimped at the ends only. Some fibers are collated to facilitate *mixing* and placing. A typical volume fraction of steel fibers is 0.25 to 1.5% (of the volume of concrete). *Aspect ratio,* defined as the ratio between the fiber length and diameter, is an important property that affects the performance of a fiber.

Steel fibers are being used since their development in the 1960s to increase the toughness, impact resistance, and flexural strength of concrete. Steel fiber-reinforced concrete is employed in airport pavements, bridge decks, industrial floors, hydraulic structures, and shotcrete application. The amount of steel fibers typically range between 0.5 and 2% by volume. The addition of steel fibers to concrete may decrease its slump as much as 50%. The concrete may exhibit dryness caused by the fact that fiber-reinforced concrete does not exhibit bleeding as much as normal concrete. In general, fibers of all kinds tend to minimize segregation, which is beneficial in both pumping and placement.

The compressive strength is very slightly affected by the addition of steel fibers. (In fact, some studies suggest that the addition of fibers may decrease the compressive

TABLE 3.14 TYPES AND PROPERTIES OF FIBERS

Type of fiber	Diameter (in.)	Modulus of elasticity (ksi)	Tensile strength (ksi)
Polypropylene	0.004-0.008	725	65
Polyester	0.0004-0.003	1,450-2,500	80-170
Polyethylene	0.001-0.04	725-25,000	29-440
Carbon	0.0003	33,000-55,000	260-380
Acrylic	0.0002-0.0007	2,600	30-140
Glass	0.0004-0.0005	10,400-11.500	360-500
Steel	0.004-0.04	29.000	50-250

strength.) An increase in flexural strength is substantially greater than that in tension or compression and is about 50 to 70% compared to the flexural strength of plain concrete. The addition of 1.5% (by volume) of fibers may increase the tensile strength by about 45%. Steel fibers have also been shown to increase the shear capacity substantially. Corrosion of fibers may be a problem with steel fiber-reinforced concrete, although studies seem to indicate that corrosion does not seem to propagate 0.10 in. (2.5 mm) below the surface.

Polypropylene and nylon fibers (synthetic) have resulted from research and development in the petrochemical and textile industries. They are characterized as "soft" fibers since individual fibers have significantly less bending stiffness (or elastic modulus) than either glass or steel fibers. When these fibers are applied at low volume percentages (less than 0.2%), no improvement in strength characteristics is seen. At percentages above 2% by volume, all strength properties have been shown to increase. Drying shrinkage cracking is also improved due to high fiber content. Studies have shown that synthetic fibers can control plastic cracking and reduce drying shrinkage cracking effectively. But the pitfalls associated with the use of synthetic fibers include low bonding and slump loss.

Alkali-resistant glass fibers are used in the manufacture of architectural panels and roofing shingles. These fibers have high tensile strength and modulus of elasticity. But the improvement in strength properties will be lost if alkalis in cement attack the glass fibers.

Fiber-reinforced concrete is used in a number of applications such as tunnel lining (shotcrete application), for rock slope stabilization, and in road and floor slabs. It is also used in the manufacture of architectural panels, roofing systems (tiles or shingles), bridge decking, storage tanks, parking floors, driveways, and precast elements. But present codes limit the use of fibers essentially to nonstructural and non-load-bearing applications except for use in slabs on grade and pavements.

3.10.4 Lightweight Concrete

Lightweight concrete is concrete with an air-dried unit weight not exceeding 115 pcf (1850 kg/m^3). Although there is more than one type of lightweight concrete, the term is generally used to identify concrete made with Lightweight aggregates. When both fine and coarse aggregates are of lightweight type, the concrete is called *all-lightweight concrete,* and when regular sand is used with coarse lightweight aggregates, the concrete is called *sand-lightweight concrete.* According to **ASTM** C330, lightweight fine and coarse aggregates are those that have dry unit weights (dry-rodded weight) less than or equal to 70 and 55 pcf (1120 and 880 kg/m^3), respectively.

Various types of lightweight aggregates were discussed earlier. The most common are pumice, scoria, expanded shale, and expanded clay. Pumice is a light-colored glassy rock of finely vesicular froth filled with elongated tubular bubbles. Scoria is a coarsely vesicular glassy rock containing more-or-less spherical bubbles. These two are commonly used in the manufacture of lightweight concrete masonry blocks, and the others are used to manufacture lightweight concrete in building construction. From the dome of the Pantheon in Rome (using pumice aggregate) to the 75-story-tall First Interstate World Trade Center building in Los Angeles (115-pcf concrete using expanded shale coarse aggregate), a number of structures have been built using lightweight concrete. The primary advantage of using lightweight concrete is its low density, which reduces the foundation weight and loads on supporting structures by two-thirds or less.

Properties. Workability is a concern in the mix design of lightweight concrete. Lightweight aggregates, since they are very porous, absorb mixing water, and may continue to absorb for several weeks. It is necessary to wet these aggregates before adding them to the mix.

As they are light, these aggregates tend to segregate and float to the surface. To improve workability and prevent segregation, it may often be necessary to limit the maximum slump (or limit the water content in the mix) and use air entrainment. Lightweight concrete is also more difficult to pump than concrete made with hard rock because the porous aggregate particles absorb water and have a rougher exterior surface. Note that concrete pumping is the standard method of placement in high-rise concrete construction. Today,, pumps have the capacity for a maximum vertical reach (in single lift) of 1400 ft (420m) or more at a volume of 170 yd^3 ($l30m^3$) per hour. Excessive mixing should be avoided in lightweight concrete manufacture because it tends to break up aggregate particles.

Compressive strength of lightweight concrete is low compared to normal-weight concrete of similar mix proportions. But by using high cement content and good-quality smaller-sized lightweight aggregates it is possible to obtain strength in the range 3000 to 5000 psi (20.7 to 34.5 MPa). The modulus of elasticity of lightweight concrete is also somewhat lower than that of normal-weight concrete.

Lightweight concrete exhibits relatively high thermal insulating value (thermal conductivity can be half as much as that of the normal-weight concrete). Concrete made with shale or clay is nearly four times more insulating than concrete made with normal aggregates. Concrete in exposed structures that suffer from alternating heating and cooling cycles should preferably use porous coarse aggregate

Compared to normal-weight concrete, lightweight concrete has higher drying shrinkage and higher creep. This is due to higher absorption and moisture movement in the concrete. However, the freeze-thaw resistance of air-entrained lightweight concrete is similar to that of air-entrained normal-weight concrete.

As pointed out earlier, the use of lightweight concrete results in substantial reduction in foundation load and usually contributes to a reduction in overall cost, even though lightweight concrete will cost more than normal-weight concrete per cubic yard.

EXAMPLE 3.12

Find the failure loads in the following two simple beams when subjected to CenterPoint loading. Use $f'\,C$ = 3000 psi and grade 50 steel. Span length 6 ft.

(a) Plain concrete beam of width 8 in., height 15 in.

(b) Reinforced concrete beam of width 8 in., height 15 in., reinforced with two No. 6 bars at a depth of 12 in. from the top.

Solution (a) Plain concrete beam:

$$\text{Modulus of rupture} = 12(f'c)0.5$$

$$= 12(3000)^{0.5}$$

$$= 657 \text{ psi}$$

$$\text{Failure moment} = \frac{(\mathbf{MOR})(I)}{c}$$

$$\text{Moment of inertia, } I = \frac{8(15)^3}{12}$$

$$= 2250 \text{ in}^4$$

$$c = 7.5 \text{ in.}$$

$$\text{Failure moment} = \frac{657(2250)}{7.5}$$

$$= \text{I97, I00 in.-Jb}$$

In a simple beam subjected to CenterPoint loading,

$$M = \frac{PL}{4}$$

where P is the load and $L$is the span length.

$$\frac{P(6x12)}{4} = 197{,}\text{lOO}$$

$$\text{Failure load, } P = 10{,}950 \text{ lb}$$

(b)Reinforced concrete beam:

$$\text{Depth of steel from compression face (top), } d = 12 \text{ in.}$$

$$\text{Area of steel, } A.< = 2(0.44)$$

$$= 0.88 \text{ in}^2$$

$$\text{Yield strength, } f_y = 50{,}000 \text{ psi}$$

$$\text{Width of beam, } b = 8 \text{ in.}$$

$$\text{Stress block depth, } a = \frac{A_s f_y}{0.85 f'c\, b}$$

$$= \frac{0.88(50{,}000)}{0.85(3000)8}$$

$$= 2.16 \text{ in.}$$

$$\text{Failure moment} = 0.88(50{,}000)(12 - 0.5 \times 2.16)$$

$$= 480{,}480 \text{ in.-lb}$$

$$\text{Failure load, } P = \frac{480.480(4)}{6 \times 12}$$

$$= 26{,}693 \text{ lb}$$

3.11 OTHER CEMENTITIOUS MATERIALS

A number of construction materials, including concrete, are manufactured using portland cement as a basic ingredient. Plaster (stucco), grout, and shotcrete are made using cement and various types of aggregates. Properties and uses of these materials are explained in this section.

3.11.1 Stucco

Stucco (or plaster) is a common construction material used as plaster on wood and masonry walls. This finish material, which is a mixture of cement, sand, and water, serves two functions:

- Appearance
- Protection

Stucco allows a variety of shapes, designs, and textures. A good plaster is incombustible, termite-proof, and exhibits excellent insulating properties.

Stucco is applied in three coats: the *scratch coat,* the *brown coat,* and the *finish coat.* The scratch coat can be applied either directly to concrete or masonry walls or on any rough surface made from woven, welded, and expanded metal lath (metal reinforcement). *Expanded metal lath* is a fabric manufactured from coils of steel that are slit and then expanded, forming a diamond pattern. *Woven wire lath* is fabricated from galvanized steel *wire.* It is fabricated with or without stiffener wire backing. *Welded wire lath* is fabricated from copper bearing cold-drawn galvanized steel wire by welding it into an intersecting grid pattern.

For direct application over masonry walls, the surface should be rough, clean, and firm. Proper suction is essential for good bonding of stucco on masonry or concrete work and also between coats. Suction is obtained by uniformly dampening, not wetting, the entire wall surface before applying the stucco.

The scratch coat is about ¾ in. (10 mm) thick. Before it hardens, the scratch coat should be crosshatched, which will act as a key for the brown coat. The scratch coat should be kept continuously wet after it sets (for at least 2 days) and then allowed to dry before applying the brown coat.

Before applying the brown coat, which is about ½ in. (10 mm) thick, the scratch coat should be dampened uniformly to provide suction. The surface is cross-scratched lightly to provide a key for the finish coat. The brown coat is kept wet for 2 days and then allowed to dry.

A 7-day interval should pass between the application of brown coat and finish coat. Before applying the finish coat, the brown coat surface should be dampened uniformly to provide suction. Finish color and texture are added to the mixture during the finish coat. The plaster should be cured: fogging is the preferred method of curing.

Fresh plaster should have good adhesion, cohesion, and workability. *Adhesion* is the capability to stick to a surface, which is influenced by aggregate, water/cement ratio, and properties of the base. *Cohesion* is the ability of plaster to stick to itself. lt is affected by the type of mix, aggregate properties (gradation and size), and mix proportions. *Workability* of the plaster is the ease with which it can be placed, shaped, floated, and troweled. It depends primarily on cohesion and adhesion of the mix.

Well-graded sand is important in the application of stucco. For base coats, coarser aggregate particles within the allowable sizes are desirable. For the finish coats, finer sizes are desirable. High-grade mineral pigments may be used in the finish coat for color effects. Normal portland cement with or without lime is used for the mix.

The proportioning standards for plaster are given in ASTM C926. Generally, l part cement, ¾ part lime, and 4 to 8 parts sand (by volume) give a satisfactory mix. Water should be sufficient to produce a plastic consistency. Excessive water lowers the strength, increases the shrinkage, cracking, and crazing, and lowers the freeze-thaw resistance. The current trend is to use a special type of cement called plastic cement, which is approximately 96% portland cement, plus a plasticizing admixture.

3.11.2 Mortar

Mortar (or masonry mortar) is a mixture of cement, lime, fine aggregate, and water. There are two types of masonry mortar:

- Lime mortar
- Portland cement-lime mortar

Lime mortar is a mixture of sand, hydrated lime, and water. The consistency of the mixture should be such that it should be cohesive and easy for troweling and should adhere to masonry units. As it is relatively weaker, lime mortar is generally used in temporary construction, from which masonry units can be salvaged and reused.

Portland cement-lime mortar is a mixture of portland cement, lime, sand, and water. The lime helps to improve the workability and increase the body (or fattiness) of the mortar. It also enhances the water retentivity of the fresh mix and the watertightness of the hardened mortar. The flexure and shear strengths of masonry (which depends on the bond strength and the strength of the units) are increased with the addition of lime.

Alternatively, portland cement mortar can be manufactured using masonry cement instead of portland cement plus lime. The addition of proper amounts of sand and water to masonry cement is all that is necessary in ordinary construction. Masonry cement, which is specially manufactured for masonry construction, is po11land cement containing some supplementary materials selected to impart workability, plasticity, and water retention. Any one or more of portland-blast furnace slag cement, portland-pozzolan cement, natural cement, slag cement, or hydraulic lime are used with normal portland cement. In addition, masonry cement usually contains one or more of the ingredients limestone, chalk, hydrated lime, and clay.

Mortar is used to bind structural masonry units together, and in so doing, acts as an adhesive and sealant. While it is true that compressive strength is the most important property of concrete, the same is not true for masonry mortar. The primary function of masonry mortar is to develop a complete, strong, and durable bond with the units. As a sealant, mortar should prevent the movement of water through the wall.

Specifications of sand for masonry mortar (ASTM Cl44) are as shown in Table 3.15. Further details on masonry mortar and its properties are given in Chapter 4.

3.11.3 Grout

Grout is a mixture of cement (or cement plus lime), fine aggregate, pea gravel [or finer coarse aggregate, generally¾ in. (10 mm) maximum]. and water and having consistency for pouring without segregation. The term *grout* is derived from the Swedish term *groot*, which means porridge. It is used to fill grout spaces in brick masonry 2 in. (5 cm) or more in horizontal dimension and in cells of hollow block masonry.

The materials are generally mixed in a mixer and poured into the grout spaces. The mixture should be cohesive without segregation, and have a slump of about 9 in. The sand used is generally of finer gradation, and as mentioned above, coarse aggregate with a maximum size of¾ in. (10 mm) is normally used. When the coarse aggregate is left out, the grout is called. Fine *grout*, and mixtures containing coarse aggregate of up to one to two times the volume of cement is called *coarse grout*. The volume of fine aggregate is generally between two and three times that of cement. Lightweight aggregates can also be used in place of gravel. Lime, up to 10% by volume (of cement), is occasionally used to increase the fluidity and to provide water retentivity.

Grout serves two functions: (1) to provide bond and (2) to increase masonry volume for bearing and fire resistance. The bond refers to the individual masonry units as well as to the reinforcement. Settlement and shrinkage, which may cause cracking in the grout and masonry, can be minimized by the use of a stiffer mix.

3.11.4 Shotcrete

Shotcrere (also called *gunite* or *pneumatically applied mortar or concrete)* refers to mortar or concrete shot into place using compressed air. The procedure is carried out using one of two methods:

- Dry mix process
- Wet mix process

TABLE 3.15 SPECIFICATIONS FOR MASONRY MORTAR

Type	Percent passing sieve no.: 4	8	16	30	50	100	200
Natural sand	100	95-100	70-100	40-75	10-35	2-15	
Manufactured sand	100	95-100	70-100	40-75	20-40	10-25	0-10

Source: ASTM Cl44. Copyright ASTM. Reprinted with permission.

In the former, dry materials (cement and aggregates) are thoroughly mixed with enough moisture to prevent dusting. The mix is forced through the hose by compressed air, and water is added at the nozzle of the gun. ln the wet process, all ingredients (including water) are premixed to produce mortar or concrete. The mixture is then forced through the hose to the nozzle, where air is injected to increase velocity. The amount of water can be regulated by a valve in the hand of the operator.

Shotcrete is commonly made with mortar mix (no coarse aggregate). In some cases, up to 25 to 30% coarse aggregate not exceeding ¾ in. (IO mm) is used. The most common method of application is the dry mix process.

A number of procedures should be followed before the application of shotcrete. The old surface (on which shotcrete is applied) should be cleaned with water under high pressure to remove dust and sand. It should be saturated at least overnight prior to the application of shotcrete. The water saturation aids in the flow of cement into the parent material. Wet curing should be done for at least 7 days after shotcreting.

Plain (unreinforced) shotcrete is relatively brittle and may crack due to pronounced tensile stresses. Shotcrete mixes are generally oversanded and therefore may require a high cement content for proper workability. This may lead to increased shrinkage cracking. Steel fibers, when introduced with shotcrete, improve the crack resistance, ductility, and energy absorption of shotcrete. Density and other properties of this material are not different from those of regular mortar or concrete. Note that proper curing of shotcrete is essential to attain the desired strength.

Shotcrete is used for tunnel and reservoir lining and swimming pools. It is increasingly made use of for repairing and strengthening of buildings, dams, and bridge piers. Other uses for shotcrete are for ground support in mining shafts, underground bulkheads, and protective coating for structural steel, masonry, and rock. One of the newest uses of shotcrete is direct application to a slope to arrest erosion (using mechanical anchors and wire mesh).

3.11.5 Soil Cement

Cement is also used to stabilize foundation soil (in pavement, buildings, slopes, etc.). *Cement-stabilized soil* (also called *soil stabilization, cement treated aggregates, rammed earth,* and *soil cement)* is produced by mixing and compacting a mixture of water, soil, and portland cement. The mixture is then allowed to cure for a time period.

Soil cement can be described as a hardened material formed by compacting soil, cement and water. The amount of cement used is between 5 to 10% by weight of soil. Almost any type of soil is suitable for soil cement or soil stabilization. A granular type of soil is preferred to clay soil. The primary application of soil cement is as a base material for flexible pavements or asphaltic pavements. The thickness of a soil cement base depends on a number of factors, including subgrade type, traffic, and thickness of wearing course. Most in-service soil-cement bases are 4 to 8 in. thick.

Soil cement is also used as an erosion-resistant facing of slopes (slope protection or slope stabilization) and as a low-permeability lining material in wastewater lagoons, settling ponds, and coal storage yards. In addition, it is used for foundation stabilization and embankments. Soil cement is also used in the manufacture of soil-cement bricks.

3.11.6 Pervious Concrete and Cement-Bonded Particle Board

Cement is the main ingredient in the manufacture of *no-fines pervious concrete*. This type of concrete, which is made with little or no fine aggregate, is used for pavement to allow rain penetration through the pavement. Fairly large void content (about 15%) makes this concrete permeable. Some compaction may be required during the placement of no-fines concrete. Curing is needed. About LO to 20% addition of sand (relative to the volume of coarse aggregate) may improve the compressive strength.

Cement-bonded particleboard is a panel material manufactured with cement, wood fibers, and very little water. The materials are mixed and pressed to produce panels comparable to particleboard or plywood. These boards are used as covering material in wood frame construction and as a base for laying floor tiles.

3.12 TESTING

A number of laboratory tests are described in this section. Following is a list of concrete properties and the corresponding test numbers.

PROPERTY	TEST NO.
Consistency of concrete, slump test	CON-1
Consistency of concrete, ball penetration test	CON-8
Unit weight and yield of concrete	CON-2
Air content of concrete	CON-2
Mixing of concrete	CON-4
Compressive strength of concrete	CON-3
Flexural strength of concrete	CON-6
Splitting tensile strength of concrete	CON-7
Modulus of elasticity of concrete	CON-5
Capping procedure	CON-9

Test CON-1: Slump Test of Portland Cement Concrete

Purpose: To determine the slump of plastic concrete.

Related standards: ASTM C143, C172.

Equipment: Slump mold, tamping rod (¾-in. diameter), pan, scale, shovel, band scoop.

Sample: Minimum 0.3 ft^3 of plastic concrete.

Procedure:

1. Start the test within 5 min. after obtaining the final portion of the composite sample.
2. Dampen the mold and place it on a flat moist pan.
3. Hold the mold firmly in place during filling (by the operator standing on the two foot pieces).
4. Fill the mold in three layers, each approximately one-third the volume of the mold.

S. Rod each layer with 25 strokes of the tamping rod. In filling and rodding the top layer, heap the concrete above the mold before rodding is started.

6. Strike off the surface by screeding and a rolling motion of the tamping rod.
7. Remove the mold immediately by raising it in a vertical direction. (The entire test, from the start of the filling through removal of the mold, should be completed within 2½ min..)
8. Place the empty mold (upside down) adjacent to the concrete sample and measure the vertical difference between the top of the mold and the displaced original center of the top surface of the specimen. This is slump.

Report: Record the slump in inches to the nearest¼in.

Test CON-2: Unit Weight, Yield, and Air Content of Concrete

Purpose: To calculate unit weight, yield, and air content of fresh concrete (gravimetric basis).

Related standards: ASTM Cl38, C172.

Definitions:

- *Yield* is the volume of concrete produced per batch, cubic yard, or cubic meter.
- *Air content* is defined as the percentage of air voids in concrete.

Equipment: 0.2-ft^3 metal cylindrical measure (bucket) (*Note:* This measure is for maximum size of coarse aggregate equal to or smaller than l in.), ¾-in. tamping rod, balance, mallet (with a rubber or rawhide head) weighing approximately l.25 lb, flat trowel.

Sample: A minimum of 0.3 ft^3 of fresh concrete.

Procedure:

1. Weigh the empty measure.
2. Fill the measure with concrete sample in three layers of approximately equal volume. Rod each layer with 25 strokes of the tapping rod. Add the final layer so as to avoid overfilling.

3. After each layer is rodded, tap the sides of the measure smartly 10 to 15 times with the mallet. (This procedure is required to release any trapped air bubbles.) After consolidation, the measure must not contain any excess of concrete protruding approximately ¼ in. (3 mm) above the top of the mold.
4. Strike off the top surface with a sawing motion of the flat trowel (using little vertical pressure).
5. Clean all excess concrete from the exterior of the measure.
6. Weigh the measure with concrete.
7. Calculate the unit weight of concrete(= W) as the ratio between net weight of concrete and volume of the measure.

$$W = \frac{\text{net weight of concrete}}{\text{volume of measure}} \quad \text{lb/ft}^3 \text{ or kg/m}^3$$

8. Calculate the total weight of all materials batched (sum of the weights of the cement, the fine aggregate, the coarse aggregate, the mixing water, and any admixture)= W_1.

$$W_1 = W_c + W_s + W_g + W_w + W_a$$

where W_c, W_s, W_g W_w, and W_a are the weights of cement, sand, gravel, water, and admixture, respectively.

9. Calculate yield as

$$\text{yield} = \frac{W_1}{27(W)} \quad \text{yd}^3\text{/batch}$$

10. Calculate the theoretical unit weight of concrete (on an air-free basis), T:

$$T = \frac{W_1}{V}$$

where V is the total absolute volume of the component ingredients in the batch in ft^3 or m^3.

$$V = \left(\frac{W_c}{3.15} + \frac{W_s}{S_s} + \frac{W_g}{S_g} + \frac{W_w}{1} + \frac{W_a}{S_a}\right) \times \frac{1}{U_w}$$

where S_s, S_g, and S_a are the specific gravities of sand, gravel, and admixture, respectively, and U_w is the density of water(= 62.4 lb/ft^3).

11. Calculate the air content as

$$\text{air content} = \frac{T - W}{T} \times 100$$

Report: Report the values of unit weight, theoretical unit weight, yield, and air content.

Test CON-3: Compression Test of Concrete Cylinders

Purpose: To determine the compressive strength of concrete.

Related standards: ASTM C39, C192, C617.

Equipment: Concrete molds, tamping rod, mallet, trowel, scoop, trowel, compression test machine.

Sample: Concrete mixed as in Test CON-4.

Procedure:

1. Place the concrete in the molds using a scoop, trowel, or shove]. (Remixing in the pan or wheelbarrow to prevent segregation is allowed.)
2. Distribute the concrete inside the mold using a tamping rod prior to consolidation.
3. Fill the mold in three equal layers, rodding each layer 25 times using a ¾-in. tamping rod.
4. Tamp the sides of the mold gently with the mallet to close any voids.
5. Finish the top surface by striking it off with the tamping rod.
6. To prevent evaporation of water, cover the specimen immediately after finishing with a sheet of impervious plastic or wet burlap.
7. Remove the specimen from the mold not less than 20 h nor more than 48 h after casting.
8. Moist cure the specimens at 73.4 ± 3° F (23 ± l°C) from the time of molding until the moment of test (by immersion in saturated-lime water or by storage in a moist room). Specimens are normally tested at I, 3, 7, and 28 days, and 3, 6, and 12 months.
9. The ends of specimens that are not plane within 0.002 in. (0.05 mm) should be capped.
10. Compression tests are made as soon as practicable after removal from moist storage. The specimens are tested in moist condition.
11. Wipe clean the bearing faces of the upper and lower bearing blocks and of the test specimen.
12. Place the specimen on the lower bearing block.
13. Carefully align the axis of the specimen with the center of thrust of the spherically seated upper block.
14. Bring the upper block to bear on the specimen. Adjust the load to obtain uniform seating.
15. Apply the load at a loading rate of 20 to 50 psi/s. (Time to failure for 3000-psi concrete is 1 to *2½* m, and for 6000-psi concrete is 2 to 5 m.)
16. Apply the load (at the designated rate) until the specimen fails.

Report: Record the maximum load. Note the type of failure and the appearance of the concrete (Fig. 3.33). Calculate the compressive strength as the average of three specimens.

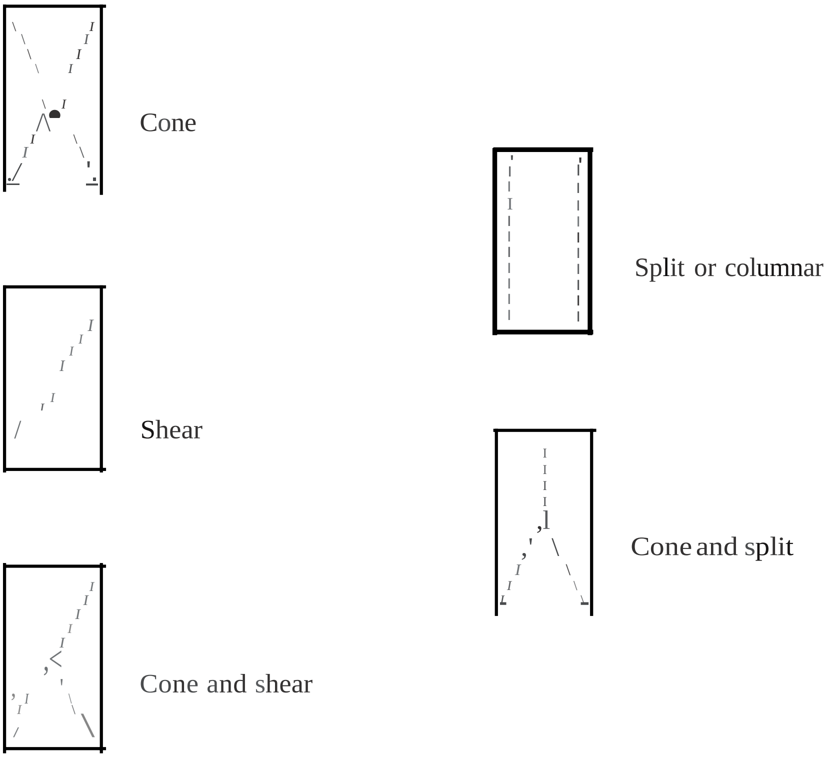


Figure 3.33 **Types** of concrete fracture.

Test CON-4: Mixing of Concrete

Purpose: Procedure to mix concrete and obtain test samples.

Related standards: ASTM Cl 92.

Equipment: Pan, tamping rod, mixer, shovel, scoop.

Procedure:

Procedure to Make Concrete Sample by Hand Mixing

1. Hand mixing should be limited to batch of 0.25 ft^3 volume or less.
2. Mixing apparatus and accessories should be cleaned thoroughly.
3. **Mix** the batch in a damp, watertight metal pan.
4. **Mix** the cement, powdered admixture (if used), and fine aggregate.
5. Add the coarse aggregate and mix the entire batch without the addition of water until the coarse aggregate is uniformly distributed throughout the base.
6. Add water, admixture solution (if used), and mix until the concrete is homogeneous in appearance.

Procedure to Make Concrete Sample by Machine Mixing

1. Add coarse aggregate, some of the mixing water, and the solution of admixture (if any) to the mixer.

2. Start the mixer.
3. Add fine aggregate, cement, and the balance of the water when the mixer is running. (If it is impractical to add these materials when the mixer is running, they may be added to the stopped mixer after permitting it to run a few revolutions following the addition of coarse aggregate and part of the mixing water.)
4. **Mix** for 3 min. followed by a 3-min. rest, followed by 2 min. of final mixing.
5. Tilt the mixer while it is running and pour the concrete into a clean and wet wheelbarrow.
6. Remove any concrete stuck in the mixer using scoop or trowel.
7. Remix concrete in the wheelbarrow using a shovel.

Test CON-5: Static Modulus of Elasticity and Stress-Strain Curve of Concrete

Purpose: To determine Young's modulus of elasticity of concrete cylinder by plotting its stress-strain curve.

Related standards: ASTM C469, C39, Cl92, C617.

Definition:

- *Young's modulus of elasticity, E is* the ratio between stress and strain within the working stress range (0 to 40% of ultimate concrete strength).

Equipment: Compression testing machine, compressometer.

Sample: 6 x 12 concrete cylinders, capped and kept in moist condition.

Procedure:

1. Determine the compression strength and unit weight of the sample using the compression specimens and procedure described in Test CON-3.
2. Attach the compressometer to the test cylinder.
3. Place the specimen (with the compressometer) on the lower platen of the testing machine.
4. Carefully align the axis of the specimen with the center of thrust of the upper block of the testing machine.
5. Lower the upper block slowly to bear on the specimen, and rotate the block gently by hand so that uniform seating is obtained.
6. Get the compressometer set up ready for deformation reading.
7. Load the specimen at a rate of 35 ± 5 psi/s.
8. Upon reaching a load of about 20% of ultimate load, reduce the load to zero (at the same rate as the loading rate), and note down the dial gage reading.

9. *If* the dial gage reading (deformation) is not zero, repeat steps 7 and 8 until the dial gage, upon unloading, is zero.
10. Start the final loading cycle and continue the loading until the maximum.
11. Record, without interruption in loading, applied load and longitudinal deformation at set intervals.
12. Calculate stress and strain as follows:

$$\text{stress} = \frac{\text{load}}{\text{cross-sectional area of cylinder}}$$

$$\text{Deformation, } d = gxl$$

where g is the dial gage reading and

$$I = \frac{e_1}{el + e_2}$$

where e_I is the eccentricity of the pivot rod from the axis of the specimen and e_2 is the eccentricity of the dial gage from the axis of the specimen

$$\text{Strain} = \frac{d}{\text{gage length}}$$

Note: Gage length is the length between gage points (generally equal to 6 in.).

13. Plot the stress-stress curve.
14. Calculate E to the nearest 50,000 psi (344.74 MPa) as follows:

$$E = \frac{S2-S1}{E_2 - 0.00005}$$

where S_2 is the stress corresponding to 40% of ultimate load, S_l the stress corresponding to a strain of 0.00005, and E_2 the strain at a stress of S_2.

Report: Report the compressive strength and unit weight of the concrete. Show the stress-strain diagram and measurement of E. Report the modulus of elasticity.

Test CON-6: Flexural Strength of Concrete

Purpose: To determine the flexural strength of concrete by the use of simple beam specimens with third-point loading.

Related standards: ASTM C78, Cl 92, C39.

Definition:

- *Modulus of rupture* is defined as the tensile strength of a material determined using a flexural specimen.

Equipment: Compression testing machine, loading (third-point) apparatus.

Sample: 6 X 6 X 20 in. flexural specimen and concrete cylinders.

Procedure:

1. Determine the compressive strength of the concrete and its unit weight using cylindrical specimens (Test CON-3).
2. Position the specimen under the bearing plate, and center the loading system in relation to the applied force.
3. Bring the load-applying block in contact with the surface of the specimen at the third points between supports (span length= 18 in.).
4. Apply the load continuously at a rate that constantly increases the extreme fiber stress between 125 and 175 psi/m (86l and 1207 kPa/m) until rupture occurs (about 2 to 6 m).
5. If the fracture occurs in the tension surface outside the middle third of the span length by more than 5% of the span length (about 1 in.), discard the result of the test.
6. Calculate the modulus of rupture **(MOR),** neglecting the beam weight, as follows:

   When the fracture initiates in the tension surface within the middle third of the span length,

   $$\textbf{MOR} = \frac{Pl}{bd^2}$$

   where P is the maximum load indicated by the testing machine, L the span length, d the beam depth, and b the beam width. For a beam with $b = 6$ in., $d = 6$ in., and $l = 18$ in.,

   $$\textbf{MOR} = 0.0833P \quad \text{psi}$$

   If the fracture occurs in the tension surface outside the middle third of the span length by not more than 5% of the span length,

   $$\textbf{MOR} = \frac{3P(a)}{bd^2}$$

   where a is the average distance between the line of fracture and the nearest support measured on the tension surface of the beam.

Report: Calculate the MOR value to the nearest 5 psi.

Test CON-7: Splitting Tensile Strength of Concrete

Purpose: To determine the tensile strength of concrete using cylindrical specimens.

Related standards: **ASTM** C496, C192.

Equipment: Compression testing machine, ¼-in.-thkk plywood bearing strips (of length slightly longer than that of the specimens and 1 in. wide); two needed.

Sample: Concrete cylindrical specimens kept in a moist condition (Test CON-3).

Procedure:

1. Determine the unit weight and the compressive strength of concrete cylindrical specimens.
2. Draw diametral lines on each end of the specimen so that they are in the same axial plane.
3. Center one of the plywood strips along the center of the lower bearing block.
4. Place the specimen on the plywood strip and align so that the lines marked on the ends are vertical and centered over the plywood strips.
5. Place the second plywood strip lengthwise on the cylinder, centered on the lines marked on the ends.
6. Apply the load continuously at a constant rate of I00 to 200 psi/m of splitting tensile stress until the failure (about 3 to 6 min./test).
7. Record the maximum load at failure, P.
8. Calculate splitting tensile strength f_t, as

$$f_t = \frac{2P}{\pi l d}$$

Report: Report the type of concrete, compressive strength, unit weight, and splitting tensile strength.

Test CON-8: Ball Penetration of Concrete

Purpose: To find the depth of penetration of a metal weight into freshly mixed concrete (as a means of determining the workability of concrete).

Related standards: ASTM C360, Cl 72, CI43.

Equipment: Ball penetration apparatus, wood float.

Sample: Concrete of minimum depth at least three times the maximum aggregate size and no less than 8 in. (20.3 mm) in a pan or wheelbarrow. The minimum horizontal distance from the centerline of the handle to the nearest edge of the level (concrete) surface on which the test is made is 9 in.

Procedure:

1. Bring the surface of the concrete to a smooth and level condition (using a wood float).

2. Set the base of the apparatus on the leveled surface with the handle in a vertical position and free to slide through the frame.

3. Lower the weight to the concrete surface and release slowly.

4. After the weight has come to rest, read the penetration to the nearest¼ in. (6.4 mm).

5. Take a minimum of three readings. If the difference between the maximum and minimum readings is more than I in. (25 mm), make additional measurements until three consecutive readings have been obtained that agree within I in.

Report: An average of three or more readings (when they agree within 1 in.) is taken as the penetration value. Report the penetration value to the nearest¼in.

Test CON-9: Capping Cylindrical Concrete Specimens

Purpose: To cap concrete cylinders (for compression test) using sulfur mortar.

Related standard: **ASTM** C617.

Equipment: Capping plate (mold), alignment device (guide bars), melting pot, exhaust fan.

Sample: Moist-cured concrete cylinders (with no moisture on the surface).

Procedure:

1. Sulfur mortar should have a minimum compressive strength, at 2 h, of 5000 psi (34.5 MPa).

2. Prepare sulfur mortar for use by heating to about 265° F (130° C). Note that the flash point of sulfur is approximately 440° F (227° C). Also, fresh sulfur mortar must be dry at the time it is placed in the pot, as dampness may cause foaming.

3. Oil the capping plate lightly.

4. Stir the molten sulfur mortar immediately prior to pouring each cap.

5. Dry the ends of the moist-cured specimens to preclude the formation of steam and foam pockets in the cap.

6. Pour the molten sulfur mortar in the plate, and lower the specimen, ensuring that the axis of the specimen is perpendicular to the plate.

7. The cap should have a thickness of about ½ in. (3 mm) and Jess than ½6in. (8 mm).

8. Remove the specimen from the plate using a slight twisting motion.

9. Cap both the ends of the specimen.

10. Maintain the specimen in moist condition between the completion of capping and the time of testing.

CHAPTER 4

Masonry

The term *masonry* refers to a construction material formed by combining masonry units such as stone and brick with a binding material called mortar. Masonry is used to build masonry wall, which is a vertical structure, thin in proportion to its length and height, that serves to enclose or divide a space and/or support other elements. Masonry is one of the oldest materials of construction; examples can be found in all parts of the world, such as the pyramids of Egypt, the Great Wall of China, several Roman and Greek ruins, the arches and vaults of Syria, and the great cathedrals of Europe.

Masonry walls can be divided into two types based on their location:

- Exterior type
- interior type

Exterior walls are those exposed to the exterior environment on at least one side. *Interior walls*, as in a wall that divides two adjacent rooms, have both sides exposed to the interior or environment.

Based on structural requirements, walls can be divided into two types:

- Load bearing
- Non-load bearing

Load-bearing walls, also called structural walls, are those designed to carry loads from other members, whereas *non-load-bearing walls* carry the self-weight only. For example, a partition wall that does not support floor or roof loads is a non-load-bearing interior wall.

Based on the method of construction, walls can be divided into two types:

- Solid wall or Hollow wall
- Framed wall

Solid and hollow walls (Fig. 4.1) are masonry walls (stone, brick or block), whereas the term *framed wall* refers to timber or metal wall. As explained earlier, a *masonry wall*, is a hollow or solid wall built by combining individual masonry units (hollow or solid) with mortar, the binding material. A *framed wall* is constructed using small sections of wood or metal joined together to provide strength and rigidity. They are finished with thin panel materials on both sides, such as plywood, gypsum board, or stucco, to fulfill the functional requirements.

Each of the above two types of walls (solid and hollow, and framed) has different characteristics that satisfy the functional requirements of the wall. One type may have good resistance to fire but may possess poor insulating properties against heat (transfer of heat). One may have poor resistance to rain penetration but good insulation against heat transfer.

Wall materials undergo dimensional changes (expansion and contraction) with changes in temperature and moisture. The stability of a wall may be affected by expansion if the movement is not accommodated in a building. Such walls should be provided with expansion joints along their length and also between the wall and the frame they are built into.

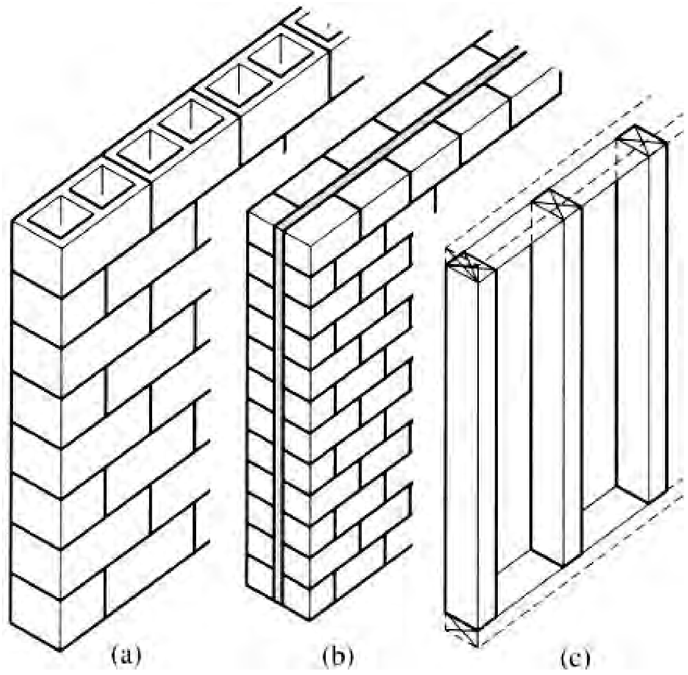


Figure 4.1 (a) Hollow and (b) solid masonry walls; (c) framed wall.

Walls are generally built as single wythe or double wythe (Fig. 4.2). *Wythe* is the portion of a wall that is one masonry unit in thickness. *Bonded wall* is the term used to identify a wall in which two or more of its wythes of masonry are adequately bonded together to act as a structural unit. When the facing and backing wythes are completely separated except for metal ties that serve as cross ties or bonding elements, there exists a cavity between the wythes, and the wall is called a *cavity wall.* The facing and backing wythes cannot be less than 4 in. (10 cm) in thickness, except when both wythes are constructed with clay or shale brick, in which case the limit is 3 in. (7.5 cm). The cavity between the two wythes must be between l and 4 in. (2.5 and 10 cm) in width. A *veneered wall* is a nonstructural wall, exterior or interior, built using facing brick, concrete, stone, tile, metal, plastic, or similar material attached to a backing for the purpose of ornamentation, protection, or insulation. An *exterior veneer* is a veneer applied to weather-exposed surfaces, and an *interior veneer* is a veneer applied to surfaces other than weather-exposed surfaces.

ln the following sections we discuss masonry construction and various masonry materials and their properties.

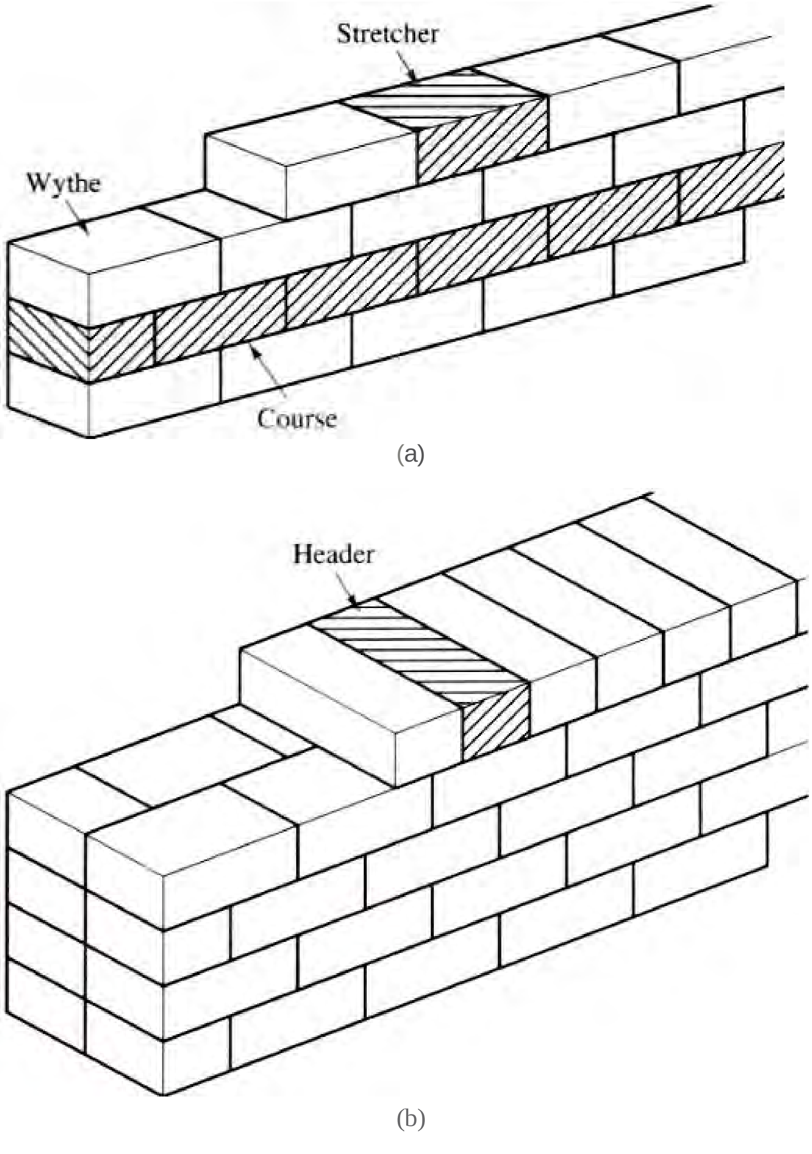


Figure 4.2ab (a) Single-wythe wall: (b) double-wythe wall.

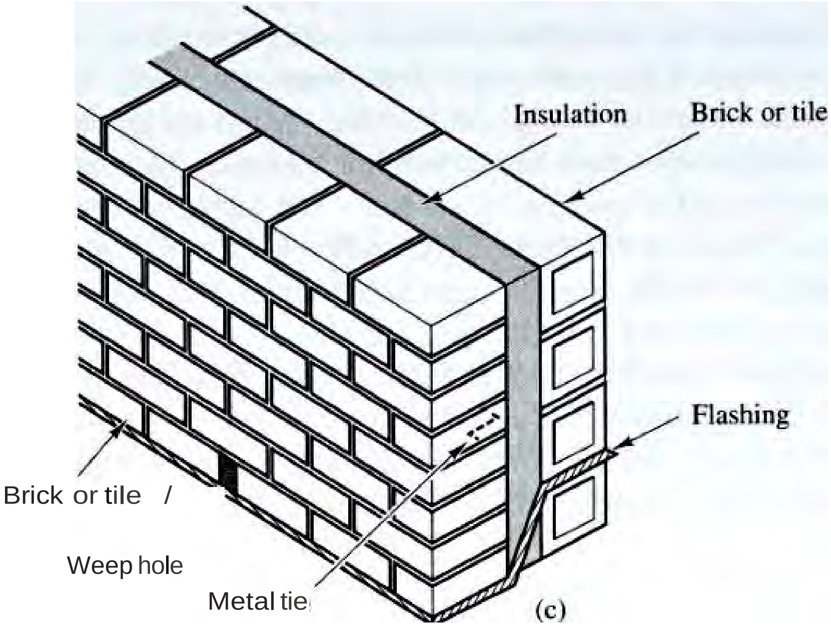


Figure 4.2c (c) Cavity wall.

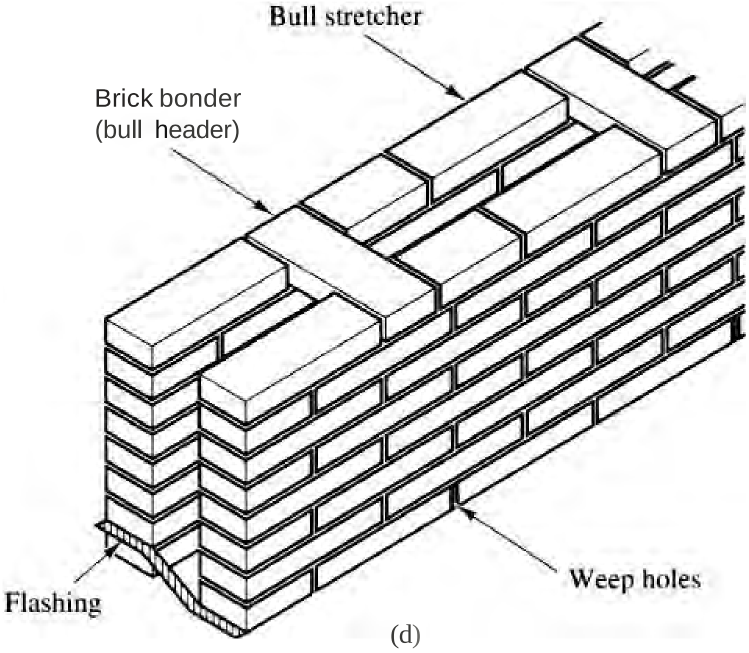
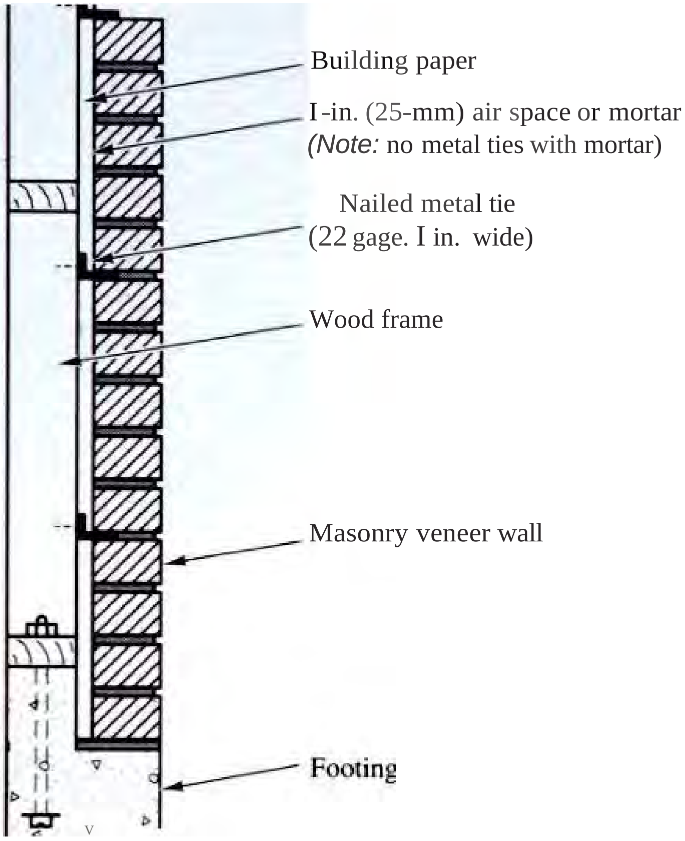


Figure 4.2d (d) Masonry-bonded hollow wall.

4.1 MASONRY UNITS

Masonry walls are built using various types of masonry units, solid or hollow, and mortar. A masonry unit is brick, tile, stone, glass block, or concrete block, conforming to certain product standards of ASTM (Fig. 4.3). A *hollow masonry Unit* is a masonry unit whose net cross-sectional area in every plane, parallel to the bearing surface, is less than 75% of the gross cross-sectional area in the same plane. A *solid masonry unit* is a masonry unit whose net cross-sectional area in every plane parallel to the bearing surface is 75% or more of the gross cross-sectional area in the same plane. Generally, a clay unit is a solid masonry unit and a concrete unit is a hollow masonry unit.



(e)

Figure 4.2e (e) Brick-veneered wall.

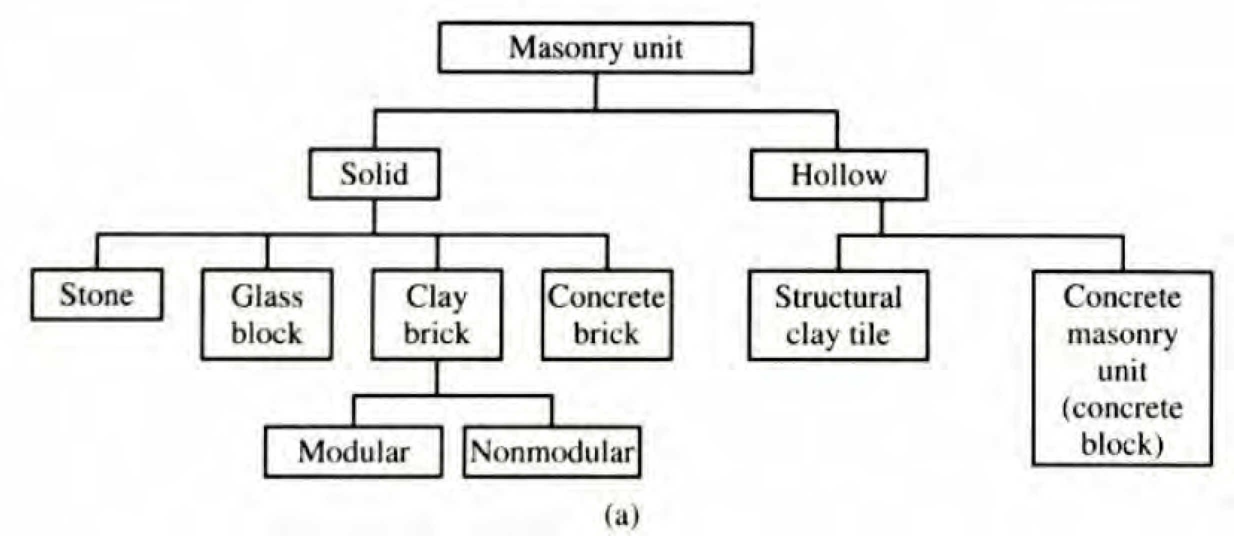


Figure 4.3a (a) Types of masonry units.

4.1.1 Clay Bricks And Structural Clay Tiles

A clay *brick* is a small solid block, usually rectangular, of burned clay (Fig. 4.4). Note that a solid block of concrete and sand-lime (calcium silicate) is also called a brick. *Structural clay tile* is a hollow clay unit, larger than the brick, and developed for use where lightweight masonry, as in filler panels and partition walls, is required.

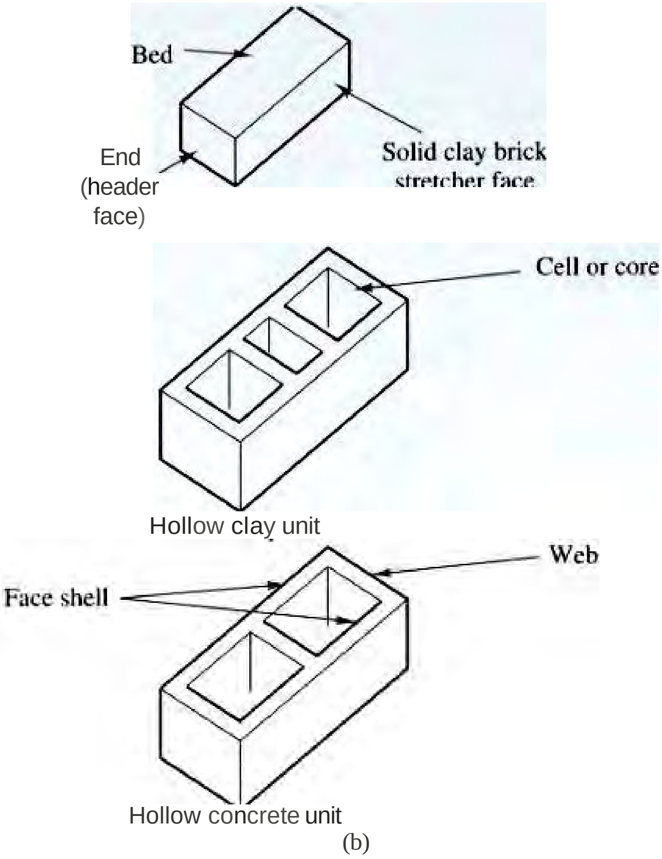
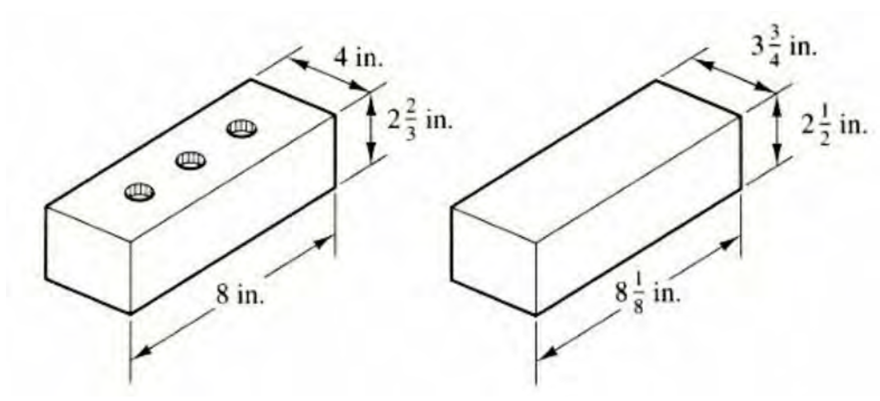


Figure 4.3b (b) Solid and hollow masonry units.

Structural tiles are also described as hollow burned clay masonry units with parallel cells or cores.

Bricks and tiles are manufactured from clay as the raw material. The word *brick* comes from the French word *brique*. Brickmaking dates back to many centuries B.C. Large brick kilns dating back to about 2000 B.C. have been found in excavations at Lothal of Ahmedabad in Gujarat state of India. The famous Ishtar Gate in Babylon, built around the end of the seventh century B.C., was faced with kiln-baked bricks bedded in bitumen.

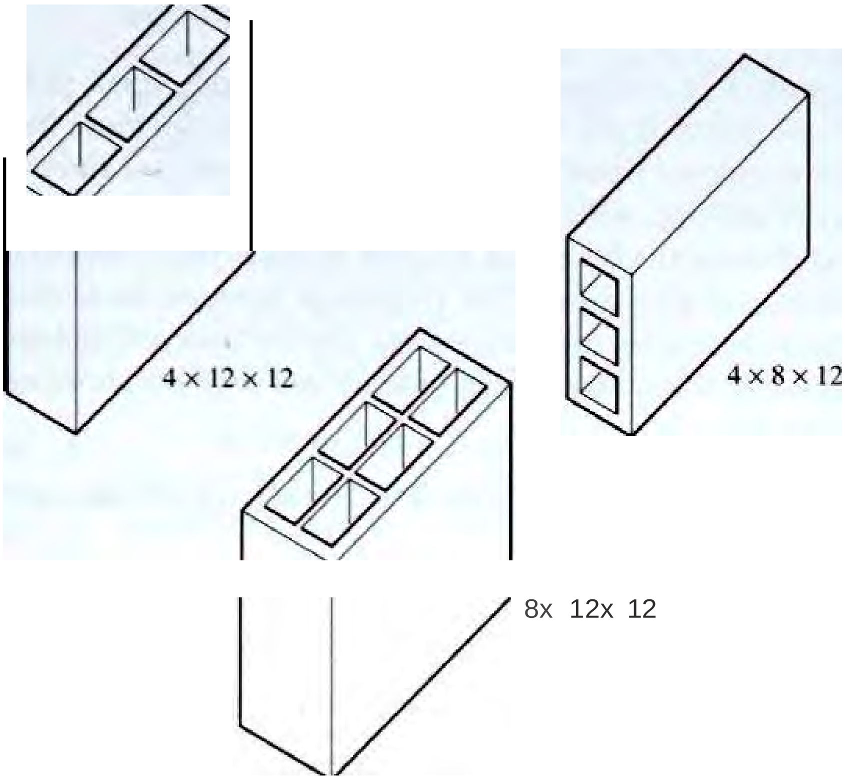
The art of brickmaking seems to have spread from Egypt to Greece and then to Rome. In Roman times the size of brick became more standardized. Many Roman



Modular brick
(Void 25% or less
of cross-sectional area)

Non modular brick
(common)

Figure 4.4a (a) Clay bricks (solid clay units).



(b)

Figure 4.4b (b) Structural clay tiles (typical nominal dimensions are shown).

bricks (well-burned broad and thin-not more than l½ in. (38 mm) thick-bricks) from the middle of the fust century B.c. onward bore a decorative motif such as an animal's head and bird. Use of bricks of nearly uniform size became common throughout Europe during the beginning of the thirteenth century. In England, there was a marked development in brick building during the middle of the fifteenth century, in which period many castles were built. Many manor homes and churches were built during the latter part of that century.

The first extensive use of bricks in the United States is around A.O. 1600 near Richmond, Virginia. A number of houses were built here, the first stories of which were of bricks made on site by brickmakers brought from England. But it is only in the last few decades that bricks have found an important role in engineered construction in the United States. Until around I 900, possibly as a result of variations in the quality of bricks, clay bricks were employed primarily in the construction of sewers, bridge piers, and tunnel linings. An exception to this is the Monadnock Building in Chicago, built around 1891, which is 16 stories tall with stone and brick walls 6 ft thick at the base and is generally cited as the last great building in the ancient tradition of masonry architecture.

Structural clay tiles are the most recently developed clay masonry units and were introduced in the United States in 1875. Their development was as a result of a need for lightweight backing material for the facing masonry used as cladding in high-rise buildings. They can be used with their webs as horizontal or vertical and for load-bearing or non-load-bearing applications. Structural clay tiles that will be plastered comes in ribbed or wire-cut texture.

4.1.2 Manufacture of Bricks

Clays for brickmaking differ widely in composition from place to place. Even in the same field, clay deposits from one part or depth may differ significantly from those from another part or depth. Clays are composed mainly of silica (grains of sand) and alumina. Alumina is the soft plastic part of the clay, which readily absorbs water, makes the clay plastic, and melts when burned. Present in all clays in addition to these two compounds are lime, iron, manganese, sulfur, and phosphates. The proportion between these compounds varies from place to place. Iron is useful in improving the hardness and strength of bricks. Lime present in clays will decompose during burning and promote shrinkage and disintegration when left in bricks.

Types of day. There are three types of clays that are used in brick manufacture:

- Surface clays
- Shales
- Fire clays

Surface clays are found near the surface of the earth. They are unconsolidated and unstratified material. They have a high oxide content, about 10 to 25%. *Shale* is also clay in its natural state, but as a result of heavy compression due to heavy soil above is quite firm and has compressed flaking characteristics. Most shales are not soluble in water except when ground, becoming plastic with the addition of water. They are costlier to remove from ground and contain large amount of fluxes.

Fire clay is a material that occurs at greater depths than either surface clays or shale. It has more uniform physical characteristics and chemical composition, and is able to withstand high temperatures. Fire clays contain less oxide (2 to 10%), which raises their softening point much higher than that of surface clays or shales. This gives refractory qualities for bricks manufactured with fire clays and ability to withstand higher temperatures.

The best material for brickmaking is clay containing about 30% sand and silt, because the presence of sand reduces the shrinkage occurring during burning of soft clays. To be molded and shaped, clays must have plasticity when mixed with water. Further, they should have sufficient tensile strength to retain the shape after forming.

Chemical analysis of clays show that they are composed principally of hydrated oxides of aluminum and iron, and hydrated silicates of aluminum. Gypsum present in clay in crystal form, as an impurity, leads to efflorescence and may also cause the bricks to crack. In brick manufacture, clays are ground or crushed in mills, mixed with water (to make it plastic and moldable), shaped to the size of a brick, textured, dried, and finally fired. Mixing of clays with water is done in pug mills. After the units are burned, they are cooled and stored for shipment.

The majority of clays burn to a red color when fired at a temperature of 900 to lOOQ°C (1650 to 1830°F). Above this temperature, the color turns to dark red or purple and then to brown or gray at about 1200°C (2200°F). Some clays may melt at this temperature. When the temperature is low, the color turns to pink or dull brown. A high iron content makes the brick salmon pink at around 900°C (I650°F), changing to darker red at higher temperatures. When lime or chalk is present in the clay, the brick may tum to white or cream.

Brick manufacture. There are three methods of manufacturing bricks and tiles:

- The Stiff-mud process
- The Soft-mud process
- The Dry press process

In the *stiff-mud process* (also called the *wire-cut process),* clay containing a minimum amount of water, generally 12 to 15% by weight, is forced through a die. The die molds the mass into desired shapes and sizes for bricks, tiles, and other products. The continuous band of clay that is forced out is later cut into bricks by a wire frame. If the cross section is the same as the end of the bricks, the bricks are called *end cut,* and if the cross section is the same as the side of the bricks, they are called *side cur.* Most bricks and structural clay tiles are manufactured using the stiff mud process, which produces the hardest and most dense of the machine-made bricks.

ln the *soft-mud process,* which is well suited to clays containing too much water in their natural state, ground clay is hydraulically pressed in steel molds. This process is used for brick. Making only and is the oldest method in brick production. All hand-made bricks are made using this process. When the insides of the mold are sanded to prevent ticking of clay. the product is *sand-struck brick.* When the molds are wetted to prevent sticking, the product is called *water-struck brick.*

The *dry press process,* which is suited for clays possessing low plasticity, consists of dropping the moist clay (mixed with about 7 to 10% water) into dry press forming machines, where the bricks are molded under low operating pressures. These use the least water in tempering and make bricks in the same way as the concrete blocks. The dry press process produces the most accurately formed bricks. It is no longer widely used because it is more expensive, due to labor costs.

The bricks coming out of forming machines contain about 7 to 30% moisture. After molding in any of the three processes the units are sent to the dryer, where they are subjected to temperatures of 110 to 300°F (43 to I 50°C) for 24 to 48 hours. Modern brick plants use dryer kilns supplied with waste heal from the exhaust of the firing kilns. After they are dried the units are baked. Baking is done in burning kilns at a very high temperature [temperature a. high as l 315°C (2400 F)l for about 40 to 150 hours. During this process parts of the clay melts and fuses the whole mass of the brick into a hard durable unit, due to alteration of the chemical structure of the clay. Burning is followed by a cooling cycle, which takes about 48 to 72 hours.

Variation in the composition of clays and the burning temperature results in a large variety of bricks. Bricks can be obtained in various colors, ranging from white to black, and can be manufactured at different densities.

4.1.3 Grades and Types

Bricks may be classified into different types, according to their uses, such as building brick (also called as common brick), facing brick, floor brick, and paving brick. *Building brick* or *common brick* is a brick for construction, not produced especially for appearance (texture and color), and used as a structural material where strength and durability are the most important requirements.

Facing brick is a brick made especially for appearance and facing purposes. This type of brick is manufactured from selected clays and available in all sizes and colors and is smooth, fine, medium, or coarse textured. Facing bricks are used for exposed areas where appearance is an important design criterion. The selection of a type of facing brick is based on color, dimensional tolerances, surface texture, uniformity, and limits on the amount of cracks and defects.

Floor brick is a smooth, dense brick, highly resistant to abrasion, used on finished floor surfaces. *Paving brick* is a low-abrasion vitrified brick, generally furnished with spacing lugs and produced in smooth or wire-cut surface finishes. They are used for roads, sidewalks, patios, driveways, and interior floors. The appearance of finished floor depends on the color, size, texture, and bond pattern of bricks. These bricks are usually uncovred, and the color ranges from red to gray and brown. *Used bricks* (also called salvaged bricks) are those having a weathered appearance and come in a broad ranges of colors.

Building bricks are manufactured in three grades (durability grades):

- Grade SW
- Grade MW
- Grade NW

Grading is based on physical requirements (minimum compressive strength, maximum water absorption, and maximum saturation coefficient) and is directly related to durability and resistance to weathering (Table 4.1). Grade SW has the highest minimum compressive strength requirement and lowest maximum water absorption. Grade NW has the lowest minimum compressive strength requirement and no limit on the water absorption. The letters SW, MW, and NW stand for severe weathering, moderate weathering, and negligible weathering. The *Annual Book of ASTM Standards* (Vol. 4.05) provides a map of general areas of the United States in which brick masonry is subject to severe, moderate, and negligible weathering.

The choice of a grade (of clay bricks) in wall construction should be based on the location of the construction in this weathering index map. The *weathering index* is the number of freeze-thaw days in a year multiplied by the winter rainfall in inches. At locations where brick masonry is subject to negligible weathering, as indicated in the map, grade MW is recommended. SW grade bricks should be used in locations that are subject to moderate and severe weathering.

In general, grade SW bricks are intended for use where high resistance to frost action is desired, such as at or below ground level. In relatively dry locations, even

TABLE 4.1 PHYSICAL REQUIREMENTS FOR BUILDING BRICK

Grade	Minimum compressive strength, gross area [psi (MPa)]		Maximum water absorption by 5-h boiling (%)		Maximum saturation coefficient	
	Average of five bricks	Individual	Average of five bricks	Individual	Average of five bricks	Individual
SW	3000 (20.7)	2500 (17.2)	17.0	20.0	0.78	0.80
MW	2500 (17.2)	2200 (15.2)	22.0	25.0	0.88	0.90
NW	1500(10.3)	1250 (8.6)	No limit	No limit	No limit	No limit

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when temperature below freezing is expected, grade **MW** bricks are recommended. Bricks in exterior face of walls above or below ground that remains dry should be of **MW** grade. Note that bricks that are exposed to exterior environment may take up moisture by capillary action. Grade NW is for use in interior construction, where no freezing occurs.

Facing bricks are manufactured in three types, based on factors that affect their appearance:

- Type FBS
- Type FBX
- Type FBA

Type FBS, which stands for *face brick standard,* is for general use in exposed masonry construction. Most facing bricks are manufactured to meet the standards of this type. *Type FBX,* which stands for *face brick extra,* is for general use in exterior or interior masonry construction where a higher degree of precision and a lower permissible variation in size than that permitted for type FBS is required. Bricks of this type are used where a high degree of mechanical perfection, narrow color ranges, and minimum permhsible variation in size are required. *Type FBA,* which stands for *face brick architecture,* is manufactured to produce characteristic architectural effects resulting from nonuniformity in size and texture of the individual units. When no type is specified, type FBS should be used. Note that these three types of facing bricks are manufactured in two durability grades: grade SW and grade **MW.**

4.1.4 Sizes of Bricks

Like concrete blocks, bricks and tiles are designated by their *nominal dimensions.* Their *specified dimensions* or modular dimensions are such that nominal measurements center to center of mortar joints will be equal to one or more standard 4-in. modules (Fig. 4.5): for example 4 in. thickness and 8 in. length, 4 in. thickness and 12 in. length, and so on. The specified dimensions are also the dimensions to which the masonry units are required to conform. The nominal dimension is greater than the specified dimension by the thickness of the mortar joint, a maximum of½ in. (12.5 mm) The *actual sizes* of bricks depend on the nominal sizes and the shrinkage occurring during the burning process.

Clay bricks are available in nominal widths (or thickness) ranging from 3 to 12 in., height or depth ranging from 2 to 8 in., and lengths up to 16 in. Brick dimensions are generally specified in a sequence of width times height times length (Fig. 4.5). For example, a nominal 4 x 2½ x 8 brick has a nominal width of 4 in., height of 2½ in., and length of 8 in. The specified or modular dimension of this unit, with a ¾-in. mortar joint is: width of 3¾in., height of 2¼ in., and length of 7¾in.

Most clays shrink during drying and burning from 4 to 15%. The amount of shrinkage depends on the fineness and the composition of clay, the amount of water in the mix, and the kiln temperature. Allowance for this reduction in cross-sectional dimensions is made during the molding process. Due to variations in the shrinkage between clays, **ASTM** specifications permit variations in dimensions of ¾2 to ¾ in. (2.4 to 9.5 mm).

The thickness of mortar joints in brick masonry varies between ¾ and ½ in. (10 and 12.5 mm). Facing bricks are generally laid in joints of thickness varying between ¾ and ½ in., and joints of building bricks are generally ½ in. thick.

Two size types are available: modular (conforming to a 4-in. grid system) and nonmodular (Fig. 4.4a). Modular bricks come in a variety of core designs (depressions),

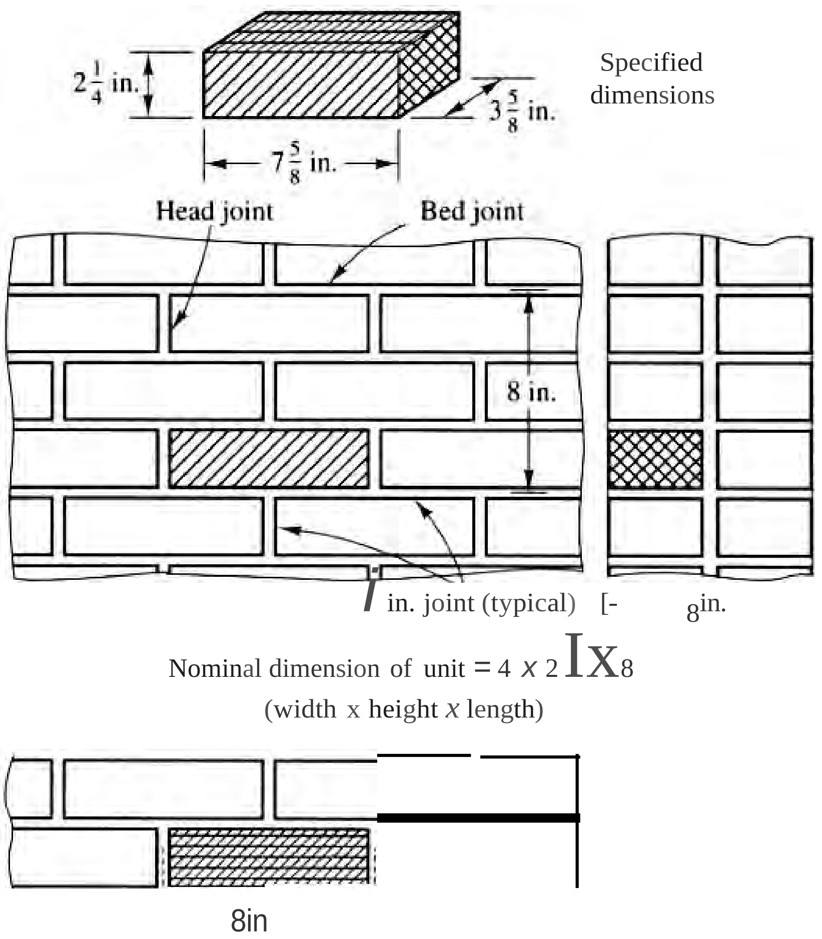

Figure 4.5 Nominal and specified dimensions.

depending on the manufacturer. Cores, originally developed to reduce the weight of a solid unit, facilitate ease of forming and handling and improve grip and mortar bond.

4.1.5 Properties of Bricks

The physical properties of clay bricks and structural clay tiles are:

- Color
- Texture
- Size
- Density

The engineering or mechanical properties are:

- Compressive strength
- Modulus of rupture
- Modulus of elasticity
- Tensile strength
- Absorption
- Thermal conductivity
- Fire resistance

A good brick should have plane faces, parallel sides, and sharp edges and angles. The texture should be uniform, and bricks should give a clear ringing sound when struck with a sharp blow. A good brick should absorb less than 20% of water by weight. It should have high compressive and bending strengths.

The brick color depends on the composition of raw materials (or presence of metallic oxides) and the degree of burning. The standard color of bricks is terra-cotta. Lime is added deliberately to provide white color to bricks. Metallic oxides (iron, calcium, and magnesium) act as fluxes to promote fusion at lower temperatures and give burned clay the necessary strength and hardness. Higher burning temperature brings in darker color as well as an increase in compressive strength. Clays containing iron oxides tum red following burning. Various color mixtures may be added prior to firing to produce different-colored bricks. The colors of bricks manufactured in the United States range from off-white to purple and black.

The texture of bricks, the surface appearance, ranges from flat to smooth and irregular. A wire-cut texture appears on two faces of bricks manufactured using the stiff-mud process. A scored finish is produced by grooving the brick surface as it emerges from the die. A combed finish is produced by penetrating the face with parallel scratches.

The density or weight of a clay unit depends on the specific gravity of the green clay, the method of manufacture, and the degree of burning. The specific gravity of clays and shales ranges from 2.6 to 2.8. The density of the burned material exceeds I 00 pcf (1600 kg/m^3), averaging 125 pcf (2000 kg/m^3).

Clay bricks are very durable and require very little maintenance. They have very good fire resistance and moderate insulating properties (against transfer of heat). The noncombustibility is an important property of bricks which is the primary reason why bricks are used in the construction of chimneys in masonry as well as wood buildings. Being porous, brick is a poor conductor. Well-built brick houses are cooler in summer and warmer in winter than are houses built of most other materials.

Absorption. Water absorption greatly affects the durability of bricks, measured by its resistance to frost action. Very soft underbumed bricks may absorb water as much as one-third of its weight, whereas good, hard bricks may absorb less than 10% of water. The smaller the amount of absorption, the greater is its durability. The saturation coefficient, defined below, is also a measure of freeze-thaw resistance. A large saturation coefficient indicates relatively fewer smaller pores in the brick. The smaller voids accommodate expansion resulting from the freezing of water in larger voids. Consequently, bricks with a higher saturation coefficient are expected to have less resistance to damaging action from frost than units having lower saturation coefficient.

Absorption of bricks (total water absorption) is defined as the increase in the weight of brick due to water, expressed as a percentage of the dry weight, and can be calculated as

$$\text{absorption} = \frac{\text{weight of water absorbed after 24 h. in cold water}}{\text{dry weight of } \textit{unit}} \times 100$$

Saturation coefficient, also called the C/B ratio, is defined as the ratio between absorption after 24 h in cold water and absorption after boiling for 5 h, and calculated as

$$\text{sat. coefft.} = \frac{\text{absorption after 24 h in cold water}}{\text{total absorption after boiling for 5 h}} \times 100$$

$$= \frac{W_2 - W_1}{W_3 - W_1} \times 100$$

where W_1 is the dry weight of unit, W_2 the saturated weight of unit after 24 hours of submersion in water, and W_3 the saturated weight of unit after 5 hours submersion in boiling water.

Highly absorptive bricks can cause efflorescence and other problems in the masonry. ASTM standards limit average absorption to a maximum 17% for grade SW and 22% for grade **MW** bricks. Most bricks have absorption of 4 to 10%. Small pores in bricks function as capillary pores which try to draw water into the unit. This action is called initial rate of absorption. The *initial rate of absorption,* also called *suction,* affects the bond. High-suction bricks remove water from mortar, affecting its curing and bond strength.

ASTM C67 shows a laboratory procedure to determine the initial rate of absorption, which should be less than 30 g/min per 30 in^2. Values of suction of clay units may range between 2 and 60 g/min. Use of bricks that have an excessive initial rate of absorption results in weak and permeable joints. Minimum water penetration and maximum bond strength are obtained with bricks having suctions less than 20 g/min. High-suction bricks, those having a suction exceeding 30 g/min, should be thoroughly wetted prior to installation, preferably 3 to 24 hours prior to their use (so as to allow rime for the distribution of moisture throughout the unit). These bricks are undesirable in load-bearing construction because they cause rapid drying of mortar and are responsible for poor bond strength and increased water penetration in the masonry.

$$\text{Initial rate of absorption} = \frac{\text{(weight of brick after 1 min. in } 1/8 \text{ in. water} - \text{dry weight of unit)}}{\text{length of unit} \times \text{width of unit}} \times 30$$

$$= \frac{W_2 - W_1 \times 30}{L \times B}$$

where W_1 is the dry weight of unit, W_2 the weight of unit after partial submersion for l min. L the length of unit, and B the width of unit.

Strength. The compressive strength of clay units depend on:

- Composition of the clay
- Method of manufacturing
- Degree of burning

Compressive strength is determined by testing individual units flatwise (load applied in the direction of the height of the unit; **ASTM** C67) and is calculated as (Fig. 4.6).

$$\text{compressive strength} = \frac{\text{failure load}}{\text{net cross-sectional area}}$$

If the net area is more than 75% of the gross area, the latter is used to calculate the compressive strength. The minimum average compressive strength of grade SW bricks is 3000 psi (20.7 MPa), those of grades MW and NW bricks are 2500 and 1500 psi (17.3 and 10.4 MPa) respectively.

The modulus of rupture is determined by supporting individual units flatwise and applying the load at the midspan in the direction of the depth of the unit on a span approximately I in. less than the basic unit length (Fig. 4.6).

$$\mathbf{MOR} = \frac{I.5Pl}{Bt^2}$$

where P is the failure load,/ the span length, and t the unit height.

Most clay bricks have a modulus of rupture anywhere between 500 and 3800 psi (3.5 and 26.2 MPa). Good hard bricks will have a MOR value in excess of 2500 psi (17.3 MPa). Soft bricks will have a MOR value close to 500 psi (3.5 MPa). The tensile strength of bricks range from 30 to 40% of the modulus of rupture. Shear values are in the range 30 to 45% of the net compressive strength.

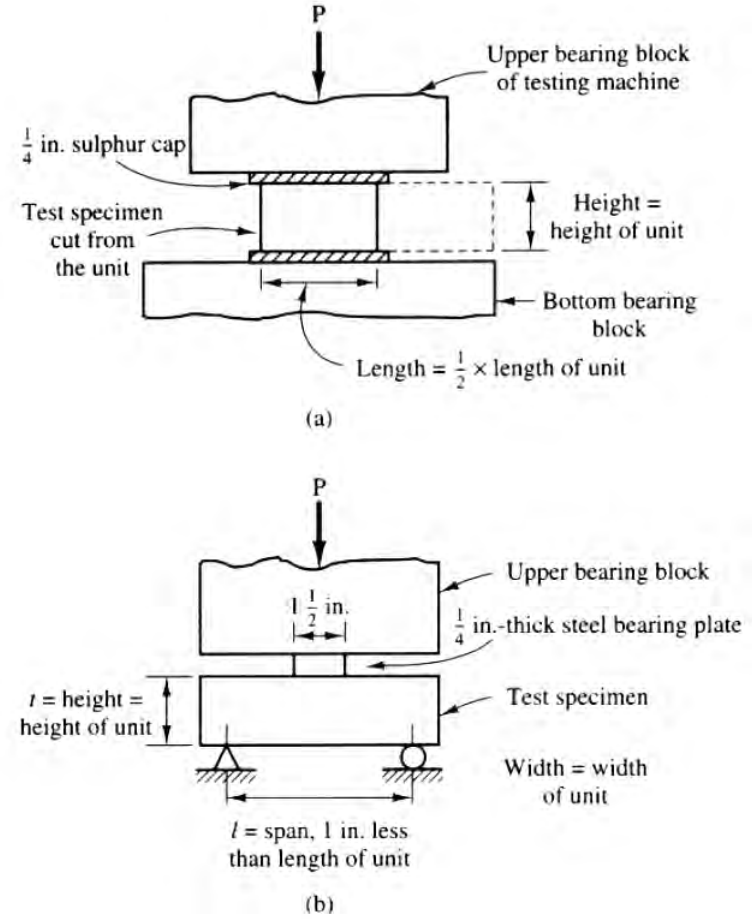
P
Upper bearing block of testing machine
$\frac{1}{4}$ in. sulphur cap
Test specimen cut from the unit
Height = height of unit
Bottom bearing block
Length = $\frac{1}{2}$ × length of unit
(a)
P
Upper bearing block
$1\frac{1}{2}$ in.
$\frac{1}{4}$ in.-thick steel bearing plate
t = height = height of unit
Test specimen
Width = width of unit
l = span, 1 in. less than length of unit
(b)

Figure 4.6 Test details: (a) compressive strength test; (b) flexure test.

The modulus of elasticity of bricks lies anywhere between 1.5×10^6 and 5×10^6 psi (10.3×10^3 and 34.5 MPa). Increase in the burning temperature or the burning period increases the modulus of elasticity. The coefficient of thermal conductivity varies between 2.8×10^{-6} to 3.9×10^{-6} per °F. The thermal expansion of brick units is between 0.30 and 0.40 in. per 100 ft a for 100°F increase in temperature.

4.1.6 Concrete Masonry Units

Concrete masonry units (also called *cinder blocks, hollow blocks,* and *concrete blocks)* are masonry units, solid or hollow, made from concrete. There are two types of concrete masonry units:

- Concrete building bricks
- Load-bearing concrete masonry units

A *load-bearing concrete masonry unit* or *concrete block* (Fig. 4.7) is a solid or hollow masonry unit made from cement, water, and mineral aggregates with or without the inclusion of other materials. The solid units have net cross-sectional area, in every

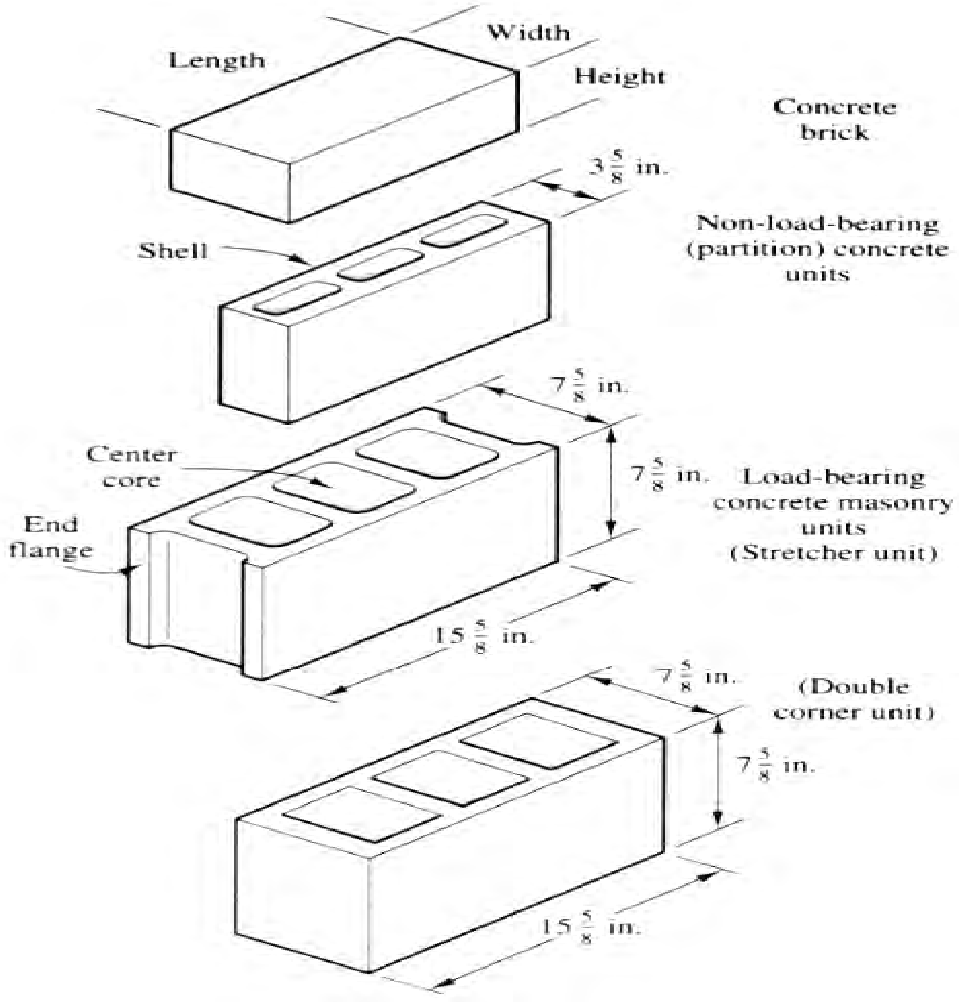

Figure 4.7 Concrete units.

plane parallel to the bearing surface, which is equal to or greater than 75% of the gross cross-sectional area measured in the same plane. A hollow unit is a unit whose net cross-sectional area in every plane parallel to the bearing surface is less than 75% of gross cross-sectional area in the same plane. [ts cross-sectional properties should conform to the minimum thickness requirements given in Table 4.2.

A *concrete building brick* is a solid masonry unit made from portland cement, water, and suitable lightweight or normal-weight aggregates with or without the inclusion of other materials. Note that this is a complete solid unit, similar in shape and size to *clay* building brick. Compressive strength of these units is considerably higher than that of load-bearing masonry units discussed above.

Both types of units-load-bearing concrete masonry unit and concrete building brick-are manufactured in three weight classifications:

TABLE 4.2 MINIMUM THICKNESS OF FACE SHELL AND WEBS OF HOLLOW MASONRY UNITS

Nominal width of units (in.)	Minimum face-shell thickness (in.)	Minimum web thickness (at the thinnest point) (in.)
3	¾	¾
4	¾	¾
6	1	1
8	I¼	1
10	I¾	1 1/8
12	I½	1 1/8

- Normal-weight units
- Medium-weight units
- Lightweight units

Normal-weight units are those weighing over 125 pcf (2000 kg/m^3) when dry, *medium-weight units* are those in the weight range of 105 and 125 pcf (1680 to 2000 kg/m^3) when dry, and *lightweight units* have weights between 85 and I05 pcf (1360 and 1680 kg/m^3). Well-graded sand, gravel, and crushed stone are used to manufacture normal-weight blocks. Lightweight units are the most common in masonry construction. They are made using lightweight aggregates such as pumice, scoria, cinders, expanded clay, and expanded shale. Lightweight units should be dry during placement because wet units will shrink substantially, due to drying causing cracks in the masonry.

The concrete masonry units are made from relatively dry mixture (zero-slump concrete) of cement, aggregates, water, and admixtures. Aggregates account for as much as 90% of the composition. The units are molded under pressure, cured under controlled conditions, and stored to continue the hydration process. Curing is done using high-pressure steam curing or low-pressure steam curing. Most units in the United States are produced using low-pressure steam curing.

Both the raw materials and the method of manufacture influence strength, appearance, density, texture, and other properties of the units. In addition to strength, density, and shrinkage, thermal, sound, and fire resistance properties of the units are affected by the use of lightweight aggregates. Lightweight blocks have higher thermal and fire resistance properties and lower sound resistance than those of normal-weight units.

Type I cement is generally used to manufacture the concrete masonry units. Type III cement is also made use of to obtain faster strength. Type IA and IHA cements are used to improve workability, compaction, and molding characteristics. Use of type A cements will also provide increased resistance to freeze-thaw cycles but may decrease the compressive strength. High-strength units are made using large amounts of cement and water (but zero slump).

4.1.7 Types and Grades of Concrete Masonry Units

Load-bearing concrete masonry units are manufactured in two types:

- *Type I:* moisture-controlled units
- *Type* II: non-moisture-controlled units

Type I units are required to comply with the moisture content provisions of Table 4.3. *Type II units* are manufactured without special consideration to controlling moisture content. Requirements in Table 4.3 recognize that inherent linear shrinkage properties of concrete in the masonry units will vary depending on material properties, manufacturing methods, and atmospheric conditions. The purpose of the moisture content requirement is to provide a method of limiting drying shrinkage of units in the masonry wall regardless of the shrinkage properties of the units (up to a maximum of 0.065%). A lower moisture content in the units is required when they are to be used in less than 50% average relative humidity (arid environment), and a higher moisture content is permitted when the units are to be placed in an environment with a relative humidity above 75% (i.e.. humid). ASTM C90 provides a map showing the mean annual relative humidity in the United States.

The primary goal of moisture content grading is to limit the shrinkage of the units due to moisture loss. In arid areas, more shrinkage will occur if more moisture, when available, will leave the units. To limit this shrinkage, in arid areas such as inland areas of California and Nevada, a lower moisture content (in the units) is required. In humid areas, such as in the coastal areas of the United States, higher-moisture-content units are required.

Selection of a type I unit is based on the moisture content in the units as delivered to the job site. This means that these units should be protected from rain or other moisture at the job site before they are placed in the wall. Units that are stored properly at the job site will achieve climactic balance and perform satisfactorily with minimum shrinkage. Units that are unprotected from rain or snow may not meet the requirements for type I units.

TABLE 4.3 MOISTURE CONTENT REQUIREMENTS FOR TYPE I UNITS

	Moisture content (avg. max.), percent of total absorption for humidity zone at job site (mean annual relative humidity):		
Linear shrinkage (%)	Humid (>75%)	Intermediate (50-75%)	Arid (<50%)
<0.03	45	40	35
0.03-0.045	40	35	30
0.04-0.065	35	30	25

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Type II units that are manufactured without special consideration given to controlling moisture content are used extensively in construction. These units should not be so moist as to cause excessive shrinkage cracks. They should be stored long enough to achieve climactic balance, which depends on the materials used, the moisture content, and the humidity conditions. Exposed type II Units may require closer-controlled joint spacing or increased horizontal reinforcement.

In addition to the moisture content requirements, both types of units should satisfy the strength and absorption requirements given in Table 4.4. Note that both types I and II units require an average minimum compressive strength of 1900 psi (13.1 **MPa)** and average maximum water absorption. The latter is a measure of total water-fillable void content in the unit and is limited to 13 to 18 pcf (206 to 288 kglm^3) (about 10 to 20% moisture content). Water absorption is determined as follows:

$$\text{water absorption in a unit} = \text{saturated weight - oven dry-weight}$$

Note that aggregates which are porous, such as lightweight aggregates, have a greater absorption than dense and nonporous aggregates, and as a result, lightweight units are permitted higher absorption than medium-weight or normal-weight units.

The compressive strength of units, based on net cross- sectional area, is required to average 1900 psi (13.1 MPa) or more. It varies between 1900 and 6000 psi (13.1 and 41.4 MPa) depending on the mix proportions. The net area is the average net area of a unit, and is calculated by determining net volume from water displacement tests described in **ASTM** Cl40. The gross area of a unit is the total area of a section perpendicular to the direction of load and can be calculated as follows (Fig. 4.8):

$$\text{gross area} = \text{actual width} \times \text{actual length}$$

The net area can be calculated as

$$\text{net area} = \text{gross area} \times \text{percentage of solid}$$

$$\text{\% of solid} = (\text{net volume/gross volume}) \times 100$$

Concrete building bricks are manufactured in two grades and two types based on strength and absorption requirements:

- Grade N (types I and ll)
- Grade S (types I and II)

TABLE 4.4 STRENGTH AND ABSORPTION REQUIREMENTS OF CONCRETE UNITS

Minimum compressive strength based on net area [psi (Mpa)]		Water absorption, max. [161b/ft^3 (kg/m^3)] by weight classification: oven-dry weight, [16lb/ft^3 (kg/m3)]		
Average of three units	Individual unit	Light weight <105 (1682)	Medium weight 105-125(1682-2002)	Normal weight >125 (2002)
1900 (13.1)	1700 (I I.7)	18 (288)	15 (240)	13 (208)

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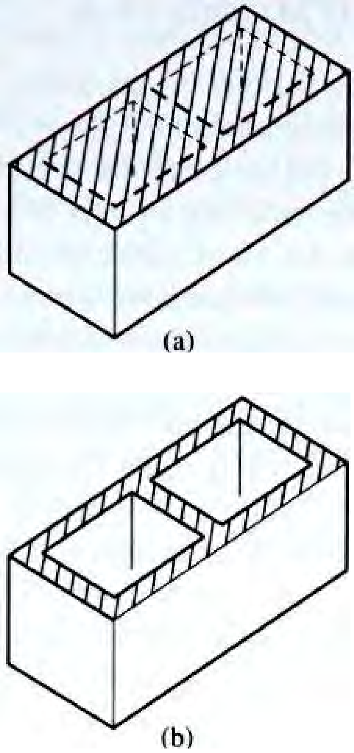

Figure 4.8 (a) Gross and (b) net areas.

The strength and absorption requirements for these two grades are shown in Table 4.5.

Grade N unit is suitable as architectural veneer or facing unit in exterior walls and for use where high strength and resistance to moisture penetration and severe frost action are required. The average maximum compressive strength of grade N bricks, when tested flatwise, should be equal to or higher than 3500 psi (24.l **MPa).** *Grade S* units are for general use where moderate strength and resistance to frost action and moisture penetration are required. Their average maximum compressive strength should be at least 2500 psi (17.3 MPa).

These two grades of concrete bricks come in two types: type I, moisture-controlled units, and type II, non-moisture-controlled units. The requirements for the units are the same as those for load-bearing masonry units shown in Tables 4.3 and 4.4.

TABLE 4.5 STRENGTH AND ABSORPTION REQUIREMENTS FOR CONCRETE BRICK

	Minimum compressive strength, [psi **(MPa)]** (based on average gross area and brick tested flatwise)		Maximum water absorption [I6lb/ft.3 (kg/m^3)] by weight classification; oven-dry weight [I61b/ft (kgtm^3)J		
Grade	Average of three bricks	Individual brick	Light weight <105 (1680)	Medium weight 105-125 (1682-2002)	Normal weight >125 (200)
N-1, N-U	3500 (24.1)	3000 (20.7)	15 (240)	13 (208)	10 (160)
S-1, S-11	2500 (17.3)	2000 (13.8)	18 (288)	15 (240)	13 (208)

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4.1.8 Properties of Concrete Masonry Units

Concrete masonry units come in various shapes, sizes, colors, and textures. Load-bearing concrete masonry units are made in nominal 4-, 6-, 8-, JO-, and 12-in. widths. They come in lengths of 12, 16, and 24 in., but the common length is J6 in. The height of the blocks is 4 or 8 in. Actual sizes of the units are usually ¾ in. (10 mm) less than the nominal dimensions. For example, a 8 x 8 x 16 in. block has dimensions: 7¾x 7½x 15¾in. Most load-bearing walls are 8 in. thick, and partition walls can be of 4 in. Concrete bricks are produced in two nominal sizes: *standard* and *modular*. The actual size of a standard concrete brick is: 3¾x 2¼ x 8 in., and that of a modular concrete brick is: 3¾x 2¼ x 7½ in.

A *split block* is a hollow concrete unit that has the appearance of rough stone texture and looks like stone masonry. It is made by breaking a double-wide unit into two pieces. It comes in various colors. A *slump block*, which looks like adobe brick in appearance, is made with a concrete mixture that is relatively more wet. During manufacture the unit is jolted, and as a result, the wet mix sags and slumps when removed from mold. The units vary in height and surface texture, but have a uniform earthtone color.

Absorption of a unit is frequently taken as a measure of its durability. Total water absorption is measured following a 24-hour period of immersion. Linear shrinkage is the change in length of a unit from a wet condition to a dry condition. It is limited to 0.065%. In masonry walls the amount of shrinkage depends on the moisture content in the units and environmental humidity. The greater the moisture content, the higher will be the shrinkage if the units are allowed to dry out in service. The shrinkage amount is also dependent on the size of the unit; The larger the size, the more the shrinkage. The amount of potential shrinkage will be a factor in predicting the amount of cracking that may occur in the walls.

Since the amount of shrinkage increases with the moisture content in the units, the concrete units should not be wet prior to being placed in the wall. But in extremely dry weather and hot temperatures, the units should be wet, using light spray, just before the placement.

As explained earlier, the compressive strength of concrete masonry units is in the range 1900 to 6000 psi (13.l to 41.4 MPa). The tensile strength lies between 250 and 500 psi (1.7 and 3.5 MPa). The modulus of elasticity varies between 1.4 x 10^6 and 4.5 x 106 psi (9.7 x 10^3 and 31 x 10^3 Mpa).

4.2 MORTAR, GROUT, AND PLASTER

Masonry walls are built using masonry units (clay or concrete) and mortar with or without grout. *Mortar* is a plastic mixture of cementitious materials, sand, and water used to bind masonry units together. The early Egyptians used a cementing material, obtained by burning gypsum, in masonry construction. Lime was used at a very early period by Greeks in the preparation of mortar.

The primary function of the mortar is to bond individual units together so that the masonry will act as a larger single unit. In addition, it serves as a bedding material for the masonry units and allows the placement of units on a leveled surface. As a binding material, the mortar is partly responsible for the strength characteristics of the masonry. Mortar- joints can be used to project some aesthetic features, such as color and appearance.

Grout is a high-slump concrete that is employed to fill the cores or voids in masonry. It is a mixture of cement, sand, fine gravel, and water. The primary function of grout is to bind the reinforcing steel and the individual wythes into a composite structural system.

Plaster is a portland cement-based cementitious mixture that is used as a finishing material for walls. It is used for masonry walls as well as framed (wood) walls.

Mortar. Mortar is a mixture of cement, lime, sand, and water. When mortar is made with lime, sand, and water it is called *lime mortar*. With the addition of cement to lime mortar, it becomes *cement-lime mortar* or simply *cement mortar*. In general, mortar is a term applied to material used for bedding, jointing, and rendering brickwork, stonework and concrete blockwork.

Cement, also called portland cement (Chapter 3) is manufactured by burning a mixture of Lime, silica, alumina, and iron oxide. Generally, type I or II cement is used with the mortar.

The term *masonry cement* refers to a hydraulic cement for use in mortars for masonry construction, containing one or more of the following materials: portland cement, portland-pozzolan cement, natural cement, slag cement, portland-blast furnace slag cement, or hydraulic lime; and in addition usually containing one or more materials such as hydrated lime, limestone, chalk, calcareous shell, talc, slag, or clay. It can be used to make mortar with or without the use of other cements or hydrated lime. Quality and performance, as well as the strength of mortar made with masonry cement, may not be as superior as that made with portland cement. Masonry cement is combined with sand and water at the job site to make mortar that meets the standards specified.

The weakest part of masonry is the mortar, and hence the less the mortar, the better. The functions of the mortar were explained earlier. It serves two important purposes: bond various units, and form cushion to distribute pressure uniformly over the surface. A thin layer of mortar is stronger than a thick one in compression. Bricks and blocks should not be merely laid, but should be rubbed and pressed down so as to force the mortar into the pores of the bricks to produce maximum adhesion.

Before it begins to set, cement mortar, has no cohesion or bonding properties. It will not stick to the edge of the brick or block. Addition of a small percent of lime makes the mortar "fat" or "rich" and more pleasant to work as it becomes more plastic. Note that the addition of lime in small amounts does not decrease the strength of the mortar or the time of set.

4.2.1 Lime and Lime Mortar

When chalk or limestone (calcium carbonate, $CaCO_3$) is burned at about 1650° F (900° C) in rotary kilns, *quicklime* (CaO) is produced. Note that calcium carbonate occurs naturally as marble, chalk, and limestone. When quicklime is slaked with minimum water, the resulting product is called hydrated lime. Lime mortar is produced by combining hydrated lime with sand and water.

$$\underset{\text{(limestone)}}{\mathrm{CaCO_3}} + \text{heat} = \underset{\text{(quicklime)}}{\mathrm{CaO}} + \underset{\text{(carbon dioxide)}}{\mathrm{CO_2}}$$

$$\underset{\text{(quicklime)}}{\mathrm{CaO}} + \mathrm{O} = \underset{\text{(hydrated lime)}}{\mathrm{Ca(OH)_2}}$$

Hydrated lime loses its water through evaporation and absorbs carbon dioxide from the atmosphere to form calcium carbonate or limestone.

$$\mathrm{Ca(OH)^2 + CO^2 = CaCO^3 + H^2O}$$

Note that when quicklime (which has a specific gravity of 2.3) comes in contact with water-slaking process-it will rapidly absorb nearly a quarter of its weight in water. The absorption is accompanied by a great rise in temperature and evolution of heat. The reaction is followed by bursting of lime into pieces, which is finally reduced to a powder. About 2½ to 3 times the volume of lime is added as water for complete slaking. The volume of powder is about 250 to 350% of the original volume of lime. This powder, called *slaked lime,* can also be used in mortar.

Hydrated lime is a dry flocculent powder resulting from hydration of quicklime in large tanks at the manufacturing plant with a minimum amount of water followed by screening and grinding. ASTM defines hydrated lime as a dry powder obtained by treating quicklime with water enough to satisfy its chemical affinity for water under the conditions of its hydration. It consists essentially of calcium hydroxide or a mixture of calcium hydroxide and magnesium oxide or magnesium hydroxide, or both. It has a specific gravity of 2.08 in pure form. It is sold in paper bags of 40 lb capacity.

Finishing hydrated lime is hydraulic lime suitable for use in plaster (in the scratch, brown, and finish coats). Two types of finishing hydrated lime are manufactured:

- Type N
- Type S

Type N is called normal hydrated lime and *type S* is called special hydrated lime, and both are suitable for finishing purposes. Type N hydrated lime has no limitation on the amount of unhydrated oxides, whereas type S has a maximum limit of 8%.

Mason's hydrated lime, hydrated lime suitable for masonry purposes, comes in four types:

- Type N
- Type S
- Type NA
- Type SA

Type N is called normal hydrated lime (for masonry purposes), *type* S is special hydrated lime, *type NA* is normal air-entraining hydrated lime, and *type SA* is special air-entraining hydrated lime. Types N and NA have no limits on unhydrated oxides, whereas types S and SA have a limit of 8% unhydrated oxides. In addition, types S and SA are distinguished by their ability to develop high early plasticity and higher water retentivity.

Hydrated lime can be more conveniently handled than quicklime and can be safely transported and stored. It is a ready material for mixing with water, sand, and cement for making mortar.

The term *air slaking* refers to the absorption of air and moisture by the exposed quicklime, resulting in calcium carbonate powder. It may also contain various proportions of oxides and hydroxides.

Hydraulic and Nonhydraulic Limes. Lime can be hydraulic or nonhydraulic. *Nonhydraulic limes* are high in calcium and are produced from carboniferous limestones and white chalk. These raw materials produce a white lime when slaked. When used in lime mortar or cement-lime mortar, nonhydraulic limes can only gain strength very slowly by taking up carbon dioxide from the atmosphere to form (extremely slowly) calcium carbonate.

Hydraulic limes and *semihydraulic limes* are produced from siliceous limestones and argillaceous limestones (containing alumina and silica in the form of hydrated aluminum silicate). When this lime comes in contact with water the silica and alumina present will combine to form insoluble compounds of cementitious value. Mortar produced from hydraulic limes gains considerable strength and will set under water. A hydraulic hydrated lime is a dry cementitious product obtained by calcining limestone containing silica and alumina to a temperature short of incipient fusion so as to form sufficient quicklime to permit hydration, simultaneously leaving unhydrated calcium silicates in sufficient quantity. This calcium silicate provides the hydraulic properties required for the powder.

Note that a nonhydraulic lime can be converted into a hydraulic lime by adding suitable materials such as pozzolans. As we described in Chapter 3, pozzolans are natural (volcanic origin) and manufactured (burned shale, burnt clay, fly ash, etc.) products, and although not cementitious by themselves, possess compounds of silica and alumina that can combine with nonhydraulic limes at ordinary temperatures in the presence of moisture to form stable insoluble compounds of cementitious value, such as calcium silicates and aluminates.

Lime Mortar. Lime mortar (produced from nonhydraulic limes) gains strength slowly. Compressive strength of lime mortar is generally in the range 100 to 400 psi (0.7 to 2.8 MPa) at 1 year. The tensile strength varies from 40 to 150 psi (0.3 to 1.0 MPa). Mortars with fine sand have higher strength than those with coarser sand. Due to the low-strength characteristics, lime mortar is not used in permanent masonry construction.

4.2.2 Mortar for Unit Masonry

As discussed earlier, the mortar performs the following functions:

- It bonds the individual units together.
- It serves as a seating material for the units.

- It allows for leveling and seating of units and seals the irregularities.
- It provides strength to the wan.
- It can be used to provide aesthetic qualities to the wall.

There are four types (grades) of mortar identified by every other letter of the word MaSoNwOrk:

- Type M
- Type S
- Type N
- Type O

All four types of mortar are prepared by mixing together cement, hydrated lime, sand, and water. Type M has the lowest amount of hydrated lime, whereas type O has the highest amount, as shown in Table 4.6. Note that either cement plus lime or masonry cement can be used in mortar preparation.

Mortar is identified by two alternative specifications:

- Proportion specifications
- Property specifications

TABLE 4.6 PROPORTION SPECIFICATION REQUIREMENTS OF MORTAR FOR UNIT **MASONRY**

		Proportions by volume (cementitious material)					
		Portland cement or blended cement	Masonry cement (type)			Hydrated lime or Lime putty	Aggregate content (measured damp, loose condition)
Mortar	Type		M	S	N		
Cement-lime	**M**					¼	
	S					over¼to½	Not less than 2¼ and not more than 3 times the sum of the separate Volumes of Cementitious materials
	N					Over½to 1¼	
	0					Over 1¼ to 2½	
Masonry cement	**M**						
	M						
	S						
	S						
	N						
	0						

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In *proportion specifications,* any one of the four types of mortars mentioned above should conform to the mixing requirements of Table 4.6. The specifications limit the maximum amount of constituent materials by volume measurement. There is no limit on water content, and the amount of water may be adjusted by the mason to provide the required workability. Aggregate content is 2¼ to 3 times the sum of the separate volume of cementitious materials used. For example, using type S mortar, with a volume of lime equal to ½ of cement volume, volume of sand is equal to 3¾ to 4.5 times the volume of cement. The mixture is not required to satisfy strength or any other requirements.

Mortar conforming to the *property specifications* is made as a mixture of cement, lime, sand, and water to satisfy the strength requirements of Table 4.7. Mortar satisfying this specification should be tested in the laboratory to determine its compressive strength, water retention, and air content. The compressive strength is usually determined by making 2-in. cubes and testing them in compression after curing the cubes for 28 days. There is no requirement on mix proportions although the volume of fine aggregate should be between 2¼ and 3½ times the net volume of cementitious materials. This property is used mainly for research purposes to determine the physical characteristics of the mortar.

4.2.3 Mixing and Properties of Mortar

Mortar mixing can be done by hand or preferably using a paddle-type mixer. Hand mixing is permitted for small batches. The procedure is to mix all the dry materials with a hoe working from one end of the wheelbarrow and then from the other. (For ease in mixing, sand and cement can be spread in alternate layers.) Next add about two-thirds of the

TABLE 4.7 PROPERTY SPECIFICATION REQUIREMENTS OF MORTAR FOR UNIT MASONRY

Mortar	Type	Average minimum compressive strength at 28 days [psi (MPa))	water retention (min%)	Air content, (max.%)	Aggregate content (measured damp, loose)
Cement lime	**M**	2500 (17.2)	75	12	
	S	1800 (12.4)	75	12	
	N	750 (5.2)	75	12-14	Not less than 2¼ and not more than 3½ times the Sum of the separate volumes of cementitious materials
	0	350 (2.4)	75	12-14	
Masonry cement	**M**	2500 (17.2)	75	18-no limit	
	S	1800 (12.4)	75	18-no limit	
	N	750 (5.2)	75	18-no limit	
	0	350 (2.4)	75	18-no limit	

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water and mix until the mixture is uniformly wet. Additional water is added until the desired workability is obtained.

A *ready-mixed mortar* consists of cementitious materials, sand, and water (with or without an admixture for set control) which are measured and mixed at a central location and delivered to the construction site for use within a period of 2½ hours. Procedure for mixing mortar in a paddle-type mixer consists of the following steps:

1. Place all the mixing water.
2. Add cement to the mixer.
3. **Mix** at low speed for 30 seconds.
4. Add lime and sand while the mixer is running.
5. **Mix** at medium speed for 30 seconds.
6. Rest for 1½ minutes.
7. Run the mixer for 1 minutes at medium speed and dump the mortar out.

Effects of mix proportions. Performance of mortar depends on its mix proportions. In addition, it is influenced by various mortar properties, such as workability, water retentivity, bond strength, compressive strength, and durability. Selection of a mortar type should be based on these properties, type of masonry units, and applicable building code requirements.

Portland cement contributes to the early strength, compressive strength, and durability of the mortar. Hydrated lime contributes to plasticity, workability, water retentivity, and reduced shrinkage characteristics. *Water retentivity* refers to a property of mortar that allows it to hold water longer, resisting the suction of dry porous masonry units. Additionally, lime provides for improved bond strength and decreased permeability. It also allows the mortar to be spread smoothly. Retempering of mortar, with the addition of lime, is easier because lime is slow setting. Sand acts as a filler material and reduces shrinkage deformations. Water is required for the plasticity in the mix.

Sand used for the mortar can be either natural or manufactured. The latter may consist of crushed stone, crushed gravel, or air-cooled blast furnace slag. Manufactured sand is characterized by particles of angular shape and rough texture that affect the workability of mortar. Both natural and manufactured sand should be graded as specified in Table 4.8. Concrete sand should not be used in mortar preparation because the maximum particle size is higher than that allowed in mortar and fewer smaller particles are available in the mix. Finer particles contribute to plasticity, water retentivity, and workability of the mix. Note that there is no laboratory testing procedure to determine the workability of mortar; the best method of measuring it is the mason's own judgment. Typically, mortar should be as wet as possible but should stay stiff enough to support the units.

Properties. As discussed earlier, the major function of the mortar is to bind the masonry units together; in so doing it acts as an adhesive and sealant. For this reason, the most important property of mortar is its ability to form a complete, strong, and durable bond with the masonry units and with the reinforcement. The capacity to bond individual

TABLE 4.8 STANDARD SPECIFICATION FOR SAND FOR MASONRY MORTAR

Sieve size [No. (mm)]	Percent passing	
	Natural sand	Manufactured sand
4 (4.75)	100	100
8 (2.36)	95-100	95-100
16 (1.18)	70-100	70-100
30 (600 µm)	40-75	40-75
50 (300 µm)	10-35	20-40
100 (150 µm)	2-15	10-25
200 (75 µm)		0-10

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units is measured by the *tensile bond strength* of mortar, which is related to the force required to separate the units.

It is important to note that although concrete and mortar are made using the same ingredients (with and without the coarse aggregate for concrete and mortar, respectively), the two are not alike in terms of their functions and requirements. What is good for concrete may not be good for mortar. Increase in compressive strength, which is the most important property of concrete, is not accompanied by a corresponding increase in tensile bond strength, which is the most important strength characteristic of mortar. Other important properties of mortar are its workability, water retentivity, compressive strength, tensile strength, and freeze-thaw resistance.

The compressive strength of mortar depends on the amount of cement in the mix. The shear and flexural strength of masonry depend on the mortar bond strength, and not directly on the compressive strength of the mortar. As explained earlier, hydrated lime improves the bond strength of the masonry and thus influences its shear and flexural strengths. An increase in lime content by 100% can increase the shear and flexural strength by as much as 100%. Note that there are no code requirements for minimum bond strength of mortar, although there are compressive strength requirements for mortars covered by the property specifications.

Type M and S mortars have higher compressive strength than that of N or O mortar. Masonry subjected to high compressive loads, high lateral loads from wind, seismic forces, or soil should be built using type M mortar. Structures below or against ground subject to severe frost action should use type M mortar.

In general, type M or type S mortar can be used for exterior walls at or below grade, such as foundation walls, retaining walls, manholes, sewers, pavements, walkways, and patios. For exterior walls above grade such as load-bearing or non-load-bearing walls and parapet walls, type N, type S, or type M mortar can be used. In interior construction such as load-bearing or non-load-bearing partition walls, any types of mortar can be used. In heavy seismic zones type N and type O mortars are not recommended.

A mortar is considered workable if it can be placed and spread with little effort and it possesses the capability to adhere to masonry units immediately after being placed. Workability is affected by water retentivity, mix, flow, and aggregate characteristics. Water retentivity is a measure of the rate at which water from mortar is lost to the masonry units. It is affected by aggregate gradation, properties of cement and lime, and air content. It can be measured using the procedure shown in **ASTM** C9**l.**

The freeze-thaw resistance of mortar is improved by air entrainment. An increase in compressive strength is also found to increase the freeze-thaw resistance and improve the durability. Mortar that has less absorption (amount of water a hardened mortar will absorb) possesses better freeze-thaw resistance than others. Tests have shown that mortar made with masonry cement absorbs less moisture and thus can better resist freeze-thaw damage.

Flow. Mortar *flow* is a property measured using a flow test and flow mold. It is the percent increase in the diameter of a conical frustrum of mortar 4 in. in diameter at its base after the flow table has been dropped through a height of½ in. 25 times in 15 seconds. For example, if the final diameter of the flow cone after the test is 8 in., the flow is 100. The *flow test* is described in ASTM C109 and C230 (Fig. 4.9). Note that flow measurement is not always accurate, as it is sensitive to the techniques of the operator and the condition of the setup.

Tests have shown that tensile bond strength of the mortar, which measures the ability of mortar to form a strong, complete bond with the units, is related to the flow as shown in Fig. 4.10. An increase in flow is generally accompanied by an increase in tensile bond strength and a decrease in compressive strength. However, in practice, there is no **ASTM** requirement for flow or bond strength measurement of mortar.

Loss of moisture from the mortar (freshly mixed) decreases its flow and thus reduces the bond strength. Retempering the mix with the addition of water does not seriously affect

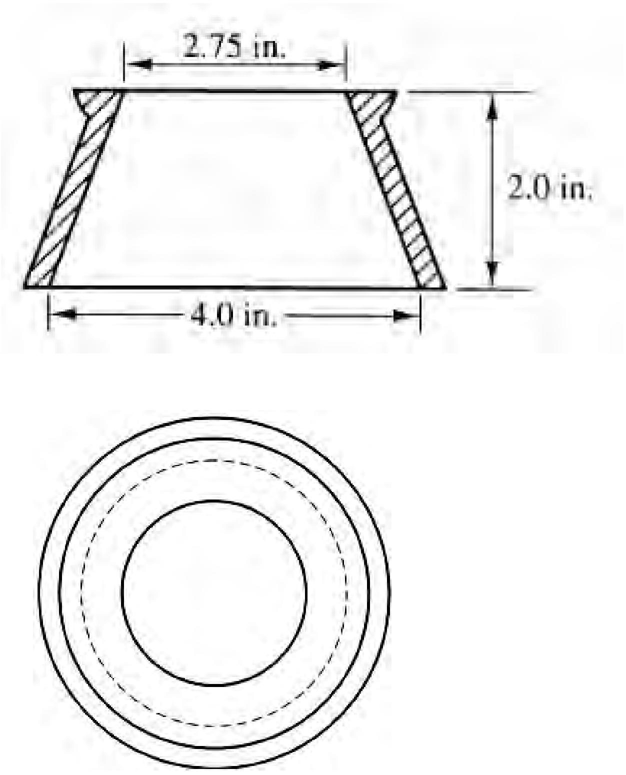


Figure 4.9 Flow Cone (mold).

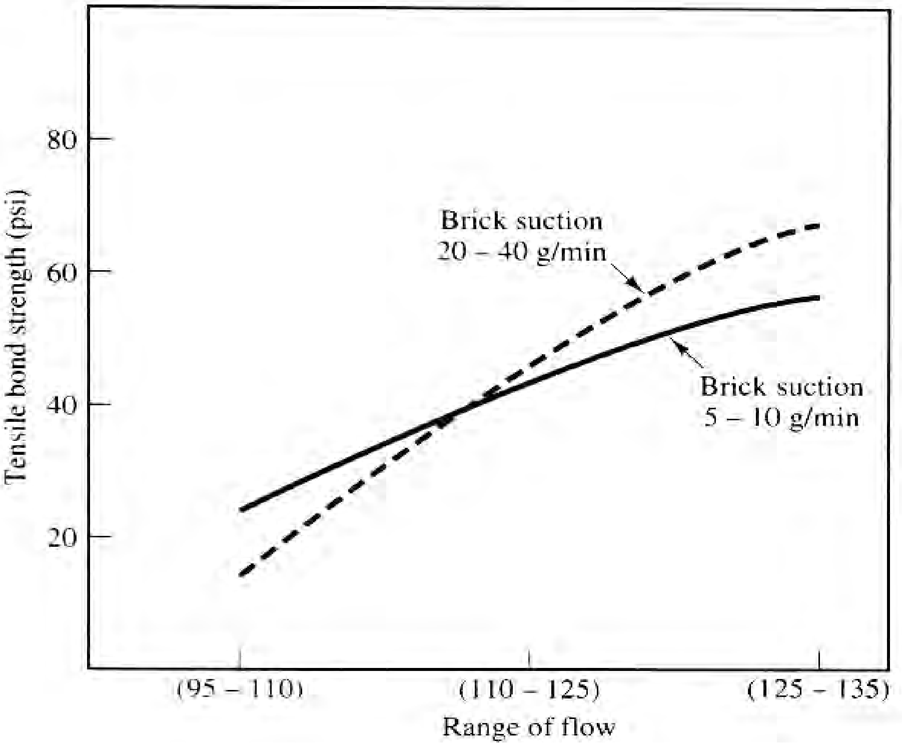


Figure 4.10 Typical variation of tensile bond strength with changes in flow.

the bond strength. The bond strength is greater when the brick suction is less than 20 g/min compared with that of bricks, with suction in the range 20 to 40 g/min.

Bond strength. The tensile bond strength can be measured using the pocedure described in ASTM C952. It ranges from 20 to 80 psi (0.14 to 0.55 MPa) for most mortars, and depends on brick suction, mix proportion, and flow. Mortars made with masonry cements are shown to exhibit excellent tensile bond strength, in excess of 100 psi (0.7 MPa). Addition of lime increases the tensile bond strength but decreases the compressive strength as well as the modulus of rupture.

Curing conditions may also affect the bond strength. When there is sufficient moisture in the mortar as bricks are laid, additional moisture from sprinkling (curing) will saturate the bricks, decreasing the adhesion between the mortar and the units. Damp curing of brick masonry is thus neither necessary nor desirable.

There seems to exist an optimum lime content, somewhere between J and ¼ parts of cement by volume, that will result in higher bond strength in a given mix. Entrained air in mortar improves the workability, water retentivity, and resistance to freeze-thaw cycles. But this improvement is generally at the expense of its tensile bond strength.

Lack of bond between mortar and masonry units allows them to separate. To check the bonding properties of mortar, lay a unit on the mortar bed and then pull it out immediately. If the mortar clings to the surface of the unit, it is an indication that the bond is adequate. Clay bricks should be wetted before placement, stone (stone masonry construction) should be dampened, and concrete masonry units should be dry to develop good bond.

4.2.4 Grout and Its Uses

As defined earlier, grout is a fluid mixture of portland cement, lime, sand, fine gravel, and water. The fluid consistency should be such that it should fill all voids in the grout space and completely encase the reinforcement. The open space between wythes or the cells in hollow units marked for grouting is called the grout space. The purposes of grout are:

- To bond individual wythes together to form a composite masonry
- To bind the reinforcement to the masonry so that the two can act as a composite material
- To increase masonry volume, which will increase bearing area and fire resistance
- To increase volume, which results in increased weight, which improves the overturning resistance of the masonry

The grout mixture is poured on top of the wall, and on its way down will fill all voids, making a solid mass of the wall (Fig. 4.11). When too much water is added to the mix, it becomes thin and results in porous or weak concrete. If the mix is dry or thick, grout will fill only the upper portion of the voids.

Aggregates for masonry grout must conform to the specifications of ASTM C404. Generally, the maximum aggregate size is ¾ in. (10 mm). High water content is required for ease of placement. One part cement, one-tenth part lime (hydrated lime or lime putty) by volume, and some sand and fine gravel are mixed with water **(ASTM** C476). Sand is typically 2¼ to 3 times the sum of the volumes of the cementitious materials. For fine grout, no gravel is used. For coarser grout, coarse gravel one to two times the sum of the volumes of cementitious materials is used. Hydrated lime should be of type S. Air-entraining admixture is not recommended for the grout in reinforced masonry construction.

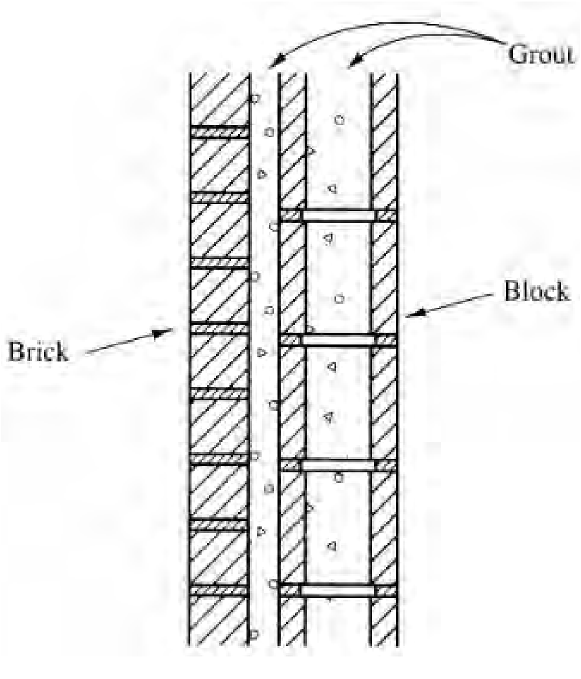


Figure 4.11 Cross section of a composite wall.

4.2.5 Plaster

Plaster is a fluid mixture of portland cement, lime, and sand which is used as a finishing material for exterior or interior walls. Stucco is plaster used as an exterior wall covering.

Stucco is applied in three coats: scratch coat, brown coat and finish coat, (Fig. 4.12). The scratch and brown coats are prepared with coarser fine aggregate and the finish coat has somewhat finer sand. Excessive fineness can cause crazing and cracking. High-grade mineral pigments such as black iron oxide, yellow iron oxide, and red iron oxide are added for color.

Each coat of stucco is made with 1 part of cementitious materials and 3 to 4 parts of damp loose sand. Average compressive strength of plaster is around 2000 psi (13.8 MPa) at 28 days. Uniform suction is necessary to achieve good bond on masonry. This is done by dampening (not soaking) the walls evenly by fog spraying before applying the stucco. In addition, wetting of the surface before plastering releases the air trapped inside the surface and consequently, helps to reduce the suction, as excessive suction can slow the hydration process. Brown and finish coats should be kept damp continuously for at

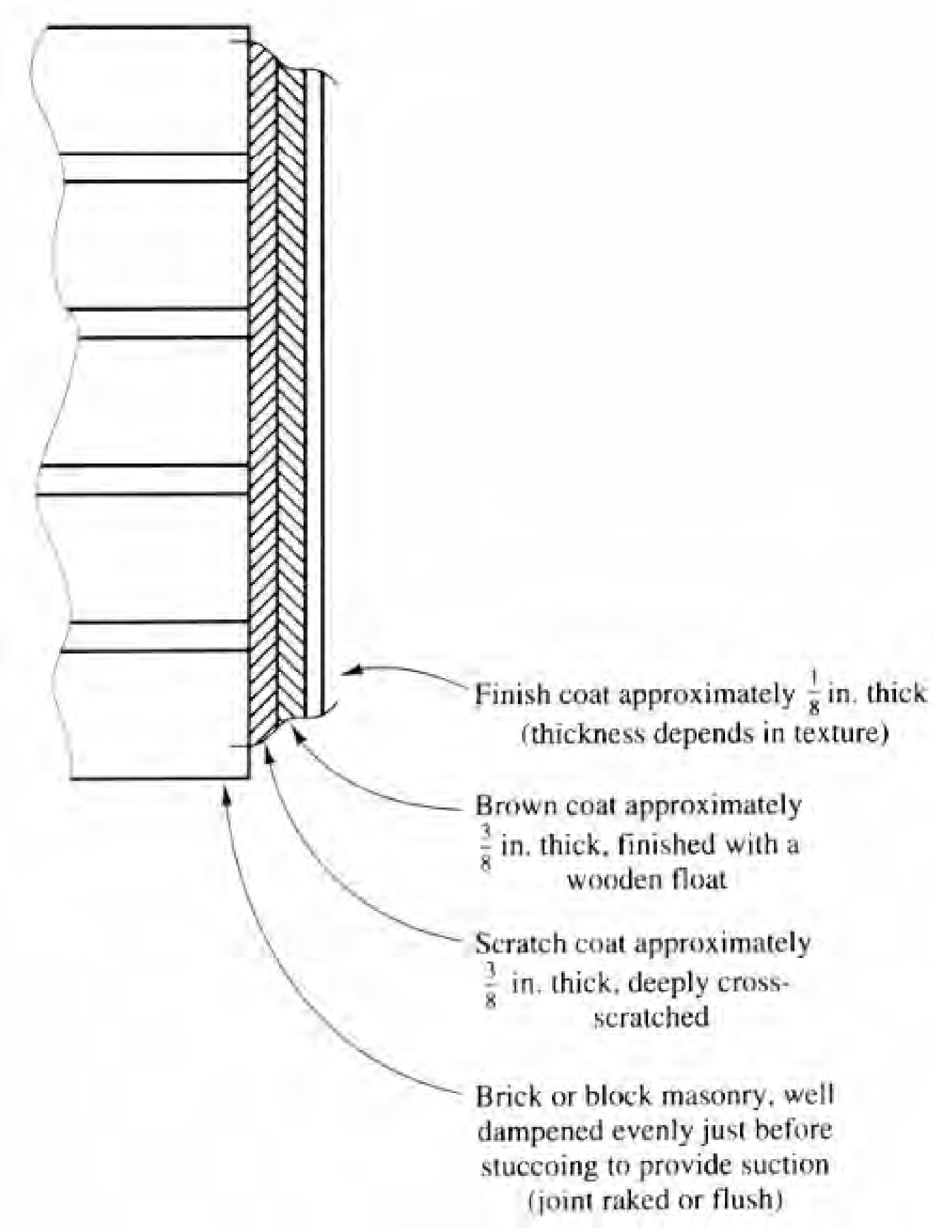

Finish coat approximately $\frac{1}{8}$ in. thick (thickness depends in texture)
Brown coat approximately $\frac{3}{8}$ in. thick, finished with a wooden float
Scratch coat approximately $\frac{3}{8}$ in. thick, deeply cross-scratched
Brick or block masonry, well dampened evenly just before stuccoing to provide suction (joint raked or flush)

Figure 4.12 Plastering on masonry.

least 2 days, starting with the hardening of the surface. Each layer should be allowed to dry thoroughly before the next coat is applied.

A mixture rich in cement should be avoided, as it tends to crack due to excessive shrinkage. Efflorescence in bricks can cause severe surface damage to the plaster. Shrinkage of the walls (concrete block walls) may cause cracking and crazing in the plaster. *Crazing* is the term used to identify small shrinkage (surface) cracks, forming a pattern on the surface. The crazed surface has an "alligator" appearance of look when it is wet. Too rapid drying and/or overworking can also cause crazing.

4.3 MASONRY CONSTRUCTION

Masonry construction is normally done by laying the bricks or blocks in a regular pattern so that each unit sits partly on two or more units. The type of procedure used for laying the units in a regular arrangement for strength and decoration is called *bond* or *bonding*.

A masonry unit is laid on its larger face, called the *bed*. A *bed joint* is the horizontal joint between two courses of brickwork. The two sides normal to the bed are called the *stretcher face* and *header face* (Fig. 4.3b). There are two stretcher faces and two header faces per unit. The header face of a clay brick is generally darker in color than the stretcher face. A *stretcher* is a unit with its long sides visible on the wall face, and a *header* is a unit with its ends that are exposed.

Procedure. The individual units are laid with mortar in a regular pattern. The mortar must be sufficiently plastic. Note that no admixtures are generally allowed with mortar or grout. The units must be placed with sufficient pressure to extrude mortar from the joint to result in a tight joint. Mortar for block wall construction is stiffer than that for brick walls. Since blocks are heavier than bricks, a wet mortar may be squeezed out of the joints when the blocks are pressed down. This may result in very little mortar left under the units and joints thinner than ½ in. (10 mm). Note that joints are typically ¾ to ½ in. (10 to 12.5 mm) thick. For a wall of certain length, the mason makes some adjustment in the thickness of head joints so that a certain number of full and half units will make up the wall length. Concrete blocks laid directly on the footing get full mortar bedding, and those laid on top of other blocks get face shell bedding only (Fig. 4.13). In *full mortar bedding*, mortar is spread onto the full thickness of the wall, and every portion of the block in the bottom row rests on mortar. In *face shell bedding*, the mortar is spread along the two outer edges only (face shell), and no mortar is spread along the webs.

The thickness of the initial bed joint must not be less than ¼ in. (7 mm) and not more than 1 in. (25 mm). Subsequent bed joints must be between ¼ and ½ in. (7 and 16 mm) thick. Solid masonry units must have full bed and head joints, and hollow masonry units have face shell bed and head joints. Improper buttering of the ends of the bricks results in weaker head joints.

Mortar and grout mixed at the job site should be mixed for a period of not less than 3 minutes and not more than 10 minutes in a mechanical mixer with the amount of water required to provide the desired workability. Mortar and grout must be used

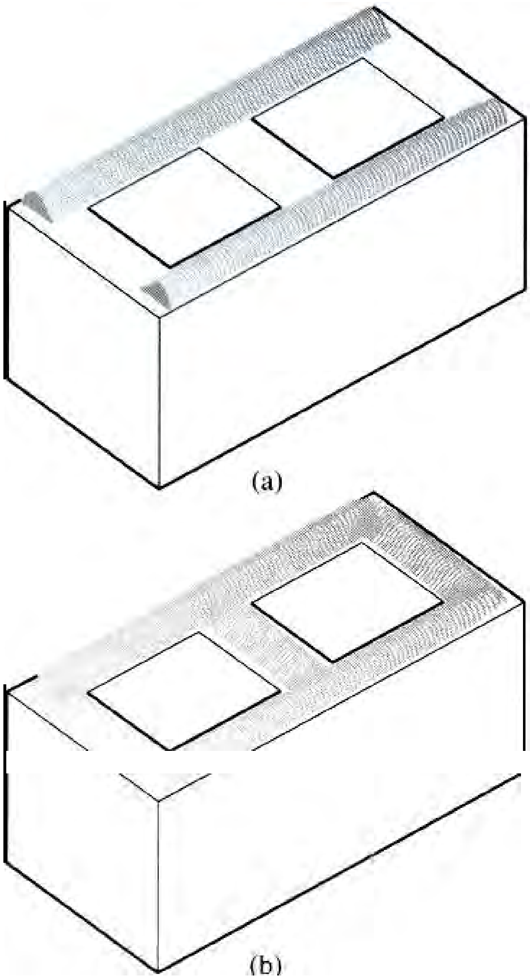


Figure 4.13 Mortar bedding: (a) face shell bedding; (b) full mortar bedding.

within 2½ hours and 1½ hours, respectively, after the initial mixing. Mortar that is more than 2½ hours old should be discarded. Within this period, mortar that is stiff can be retempered, and in this process the mortar is mixed with additional water to compensate for evaporation loss.

Concrete blocks and clay bricks should be laid on concrete footing, which is generally about twice as wide as the wall thickness (Fig. 4.14). For example, for a brick or block wall that is nominal 8 in. (20 mm) wide, the width of footing is 16 or 18 in. (40 or 45 mm). For retaining walls, footing should be larger. The depth of footing should be a minimum of the wall width. Every footing should be below the frostline. For clay brick walls, the footing can also be done using clay masonry instead of concrete.

The footing should be dampened before spreading the mortar on its top. First, corner blocks are laid on the footing at each corner, followed by one or more corner blocks on top of them (Fig. 4.15). Each successive course of corner blocks is laid so that the blocks overlap each other to form a running bond. Intermediate blocks are laid following the placement and leveling of two or more courses of corner blocks. The intermediate blocks have to be buttered at their ends before being laid. All adjustments in positioning the blocks should be carried out while the mortar is still plastic. Later adjustments will break the mortar bond.

To make watertight joints, concrete masonry units should have full mortar bedding on the face shells. The units should be pushed into place when laying so that excess

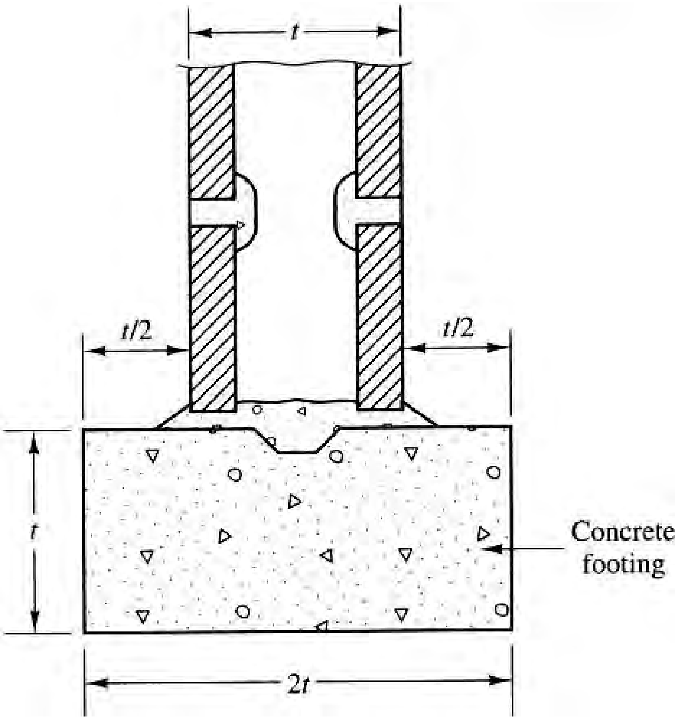


Figure 4.14 Footing dimensions (*t* = wall thickness.

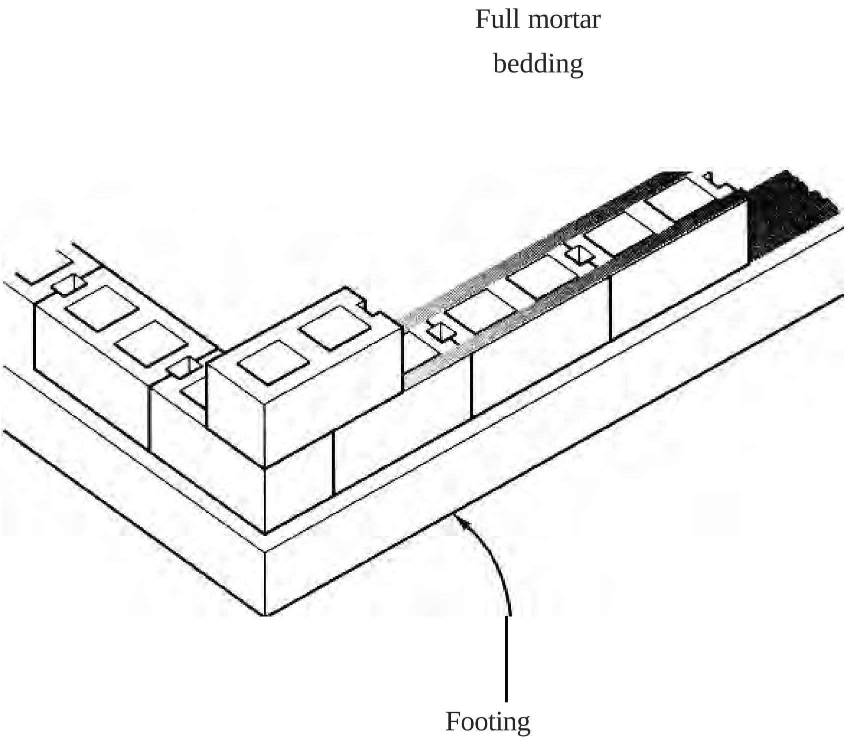


Figure 4.15 Masonry construction.

mortar squeezes out at the head joint and at the sides of the wall. The head joint must be completely filled with mortar. After the unit is bedded, the excess mortar is cut off and used for the next end joint. Surplus mortar is thrown back to the mortar board. Before the mortar sets, the wall should be checked vertically, horizontally, and along an angle to see that all the units are aligned, leveled, and plumb. If they are not, adjustment can be made by taking the offending units. Once the mortar is set, units should not be moved; they have to be relaid. In the case of double-wythe walls. both wythes should be built at the same time. Their head joints should be staggered between the two wythes, and all courses should be level with each other (Fig. 4.5). Tool finishing of joints should be delayed until the mortar is sufficiently stiff to hold the shape.

Masonry units should be stored so that at the time of use they are clean and structurally suitable for the use intended. The rate of absorption of clay units, when held in ½-in.-deep water for 1 minute should not exceed 0.025 ounce per square inch. Uniform suction of units is necessary to achieve good bond with mortar. Clay units have greater affinity for water, and it is best to dampen them before laying. If the mortar is stiff and the brick is dry, the latter will dry out the mortar before it can set or harden. To control the suction, concrete units should be kept dry until they are built into the wall and clay units must be dampened.

Partially completed walls should be covered at all times when work is not in progress. Prior to grouting the grout space must be clean without any mortar projections greater than ½ in (12.5 mm), mortar droppings, and foreign material. Grouting of any section of wall must be completed in 1 day with no interruptions greater than 1 hour.

A brick-veneered wall (Fig. 4.2d), which is one-wythe thick, provides weather-tightness and low maintenance. It needs a wider foundation than that for a framed or solid brick wall (about 4½in. (11.5 cm) additional width). This type of wall is laid with no headers but should be tied to the frame. A common method of tying is to nail 22-gauge corrugated metal ties to the frame and bend them down into mortar joints as the bricks are laid. One tie for every 2 ft^2 (0.19 m^2) of wall area is recommended, and the maximum spacing between the ties, both horizontally and vertically, is 24 in. (61 cm). Note that before laying the bricks, a layer of building paper should be stapled to the frame (sheathing).

Grouting. Based on the extent of grouting, a block wall is classified as a partially grouted wan or solid grouted wall. A *partially grouted wall* is a wall in which grout is confined only to those cells that have horizontal or vertical steel (Fig. 4.16). The partial

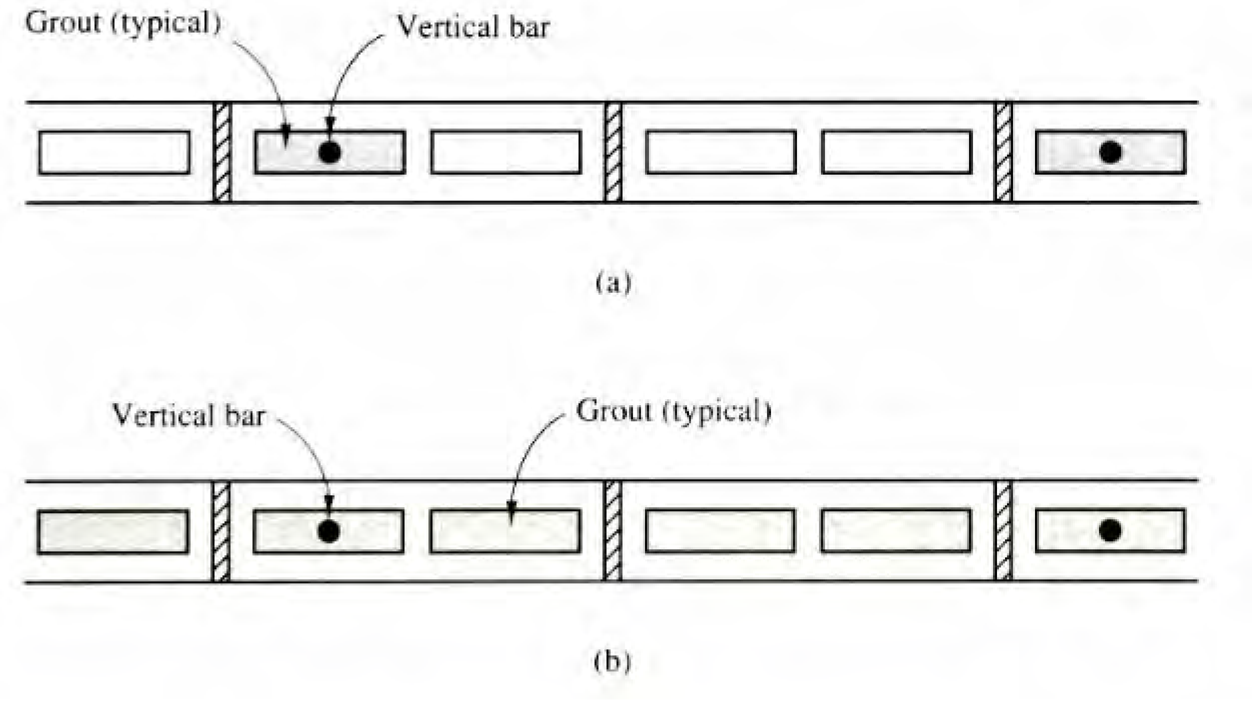


Figure 4.16 (a) Partially grouted wall; (b) solid grouted wall.

grouting technique reduces the dead load and the quantity of grout. Expanded wire mesh is placed on the bed joints below (and sometimes above) the horizontal steel to confine the grout to cells with steel reinforcement. In addition, to prevent grout from flowing between joints in neighboring empty cells, cross webs of units should be bedded.

A *solid grouted wall* is a wall in which all cells are filled with grout, and the wall is a solid masonry wall. Due to the increased cross-sectional area, a solid grouted wall possesses greater load-carrying capacity than that of a partially grouted wall. It also has increased fire rating and provides greater stability against overturning. But it is more expensive than a partially grouted wall and is heavier, requiring heavy foundation.

Low-lift grouting is a method of grouting where the height of grout pour is 5 ft (1.5 m) or less. Cleanouts are not required in this method of construction. *High-lift grouting* is a method of grouting where the height of masonry prior to grouting exceeds 5 ft. (1.5 m) Cleanouts should be provided in this method of construction. *Cleanouts* are openings placed at the bottom of hollow masonry walls for the removal of mortar droppings and other debris (Fig. 4.17). They are provided by a number of means, such as leaving out a unit, removing face shells, or cutting holes in the face shells.

In two-wythe masonry construction, when the grout pour height exceeds 12 in. (30 cm), the wythes should be tied together with metal ties to prevent them from bulging (Fig. 4.18). This procedure is required in both low-lift and high-lift grouting techniques. Note that hollow unit masonry does not require ties. The spacing of ties in running bond construction is 24 in. (61 cm) in horizontal direction and 16 in. (40 cm) in vertical direction.

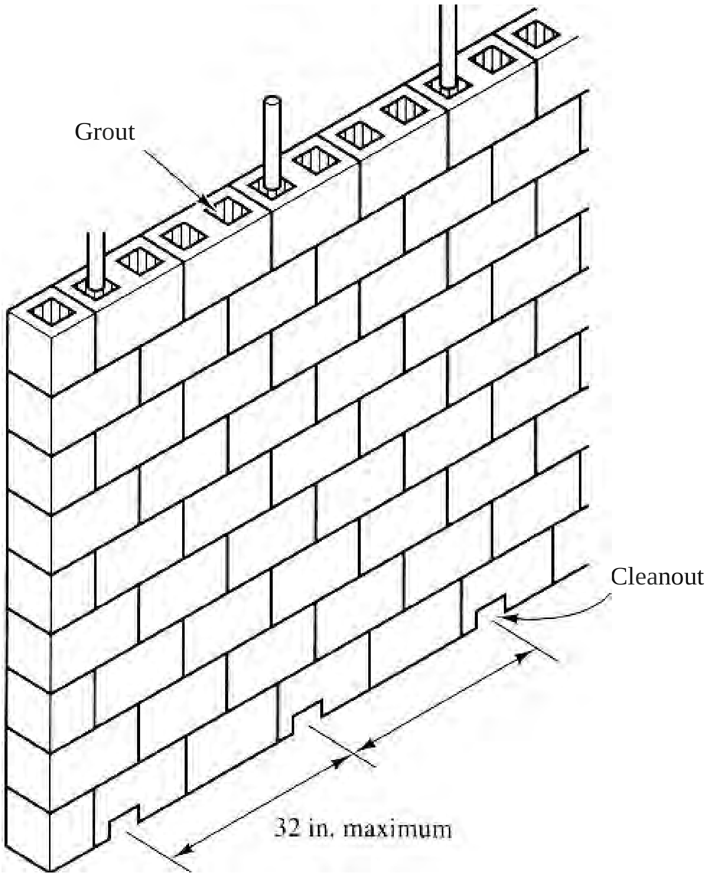


Figure 4.17 Cleanouts in a solid grouted wall.

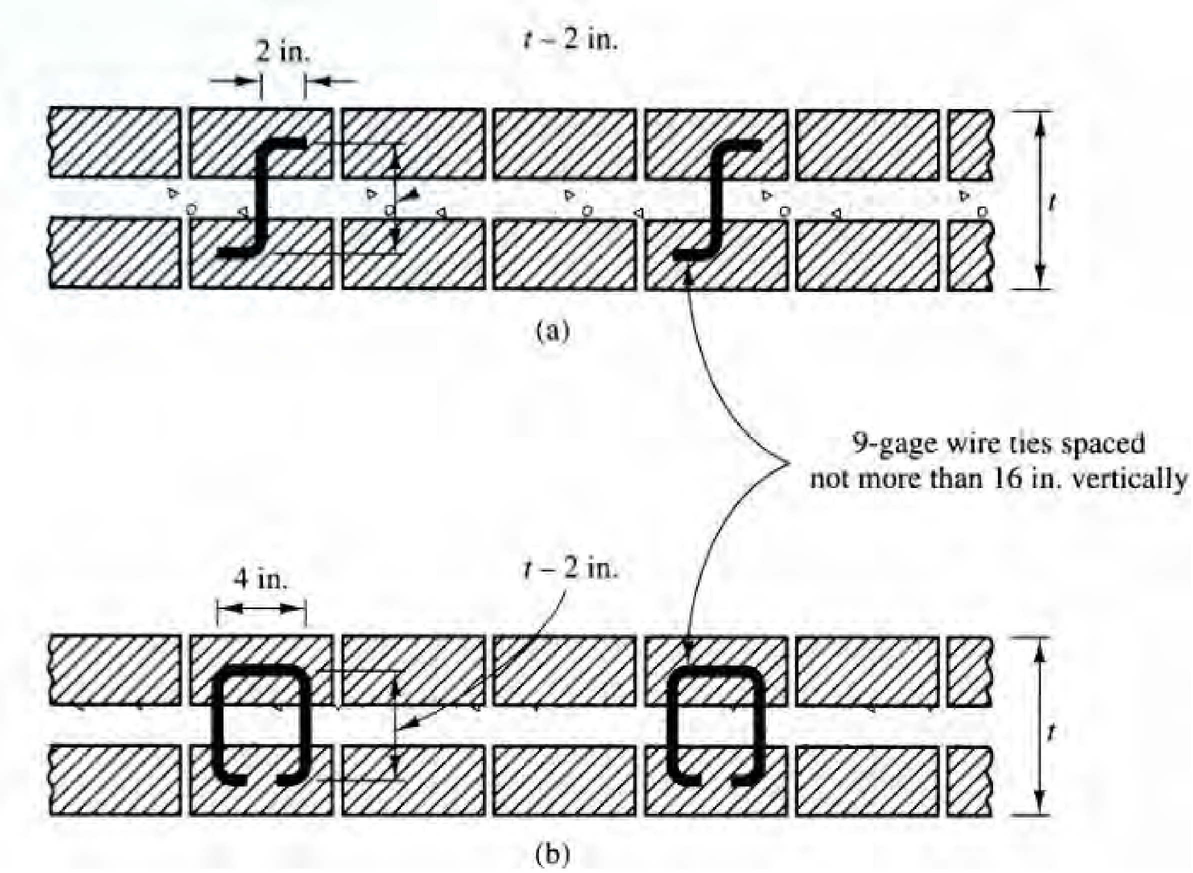


Figure 4.18 Bonding of double-wythe walls: (a) zee tie; (b) rectangular tie.

4.3.1 Types of Bond

As explained earlier, bond (also called *pattern bond)* refers to the type of procedure used in laying the units. When the bricks are laid on bed with every brick showing a stretcher face or long face on each side of the wall, it is called *stretcher bond* (Fig. 4.2a). Note that the stretcher units bind the wall together lengthwise and the header units crosswise. When the bricks are arranged so that every brick shows a header face or short face on each side of the wall, it is called *header bond.*

Running bond is the simplest system of laying bricks and consists of all stretchers or stretcher bond (Fig. 4.19). It is used commonly in cavity wall, veneer wall, and facing tile wall construction. Since there are no headers, metal ties should be used for tying.

A *block* or *stack bond* consists of no overlapping units, and all vertical joints are aligned. Due to inadequate lateral strength, this type of wall is usually bonded to the backing with rigid steel ties.

When a combination of header bond and stretcher bond is used, the procedure comes under *English bond, Flemish bond,* or *common bond* (Fig. 4.19). In English bond the bricks in one layer are laid on header bond and the courses above and below this are laid on stretcher bond. There are twice as many vertical or side joints in a course of headers as there are in a course of stretchers. This bond is very strong because of the absence of straight joint within the vertical section of the wall. But the pattern is more difficult to lay and is more expensive than other bonds.

In Flemish bond, bricks in every course show, alternately, header and stretcher bonds. The outer end of each header lies in the middle of a stretcher in the course below.

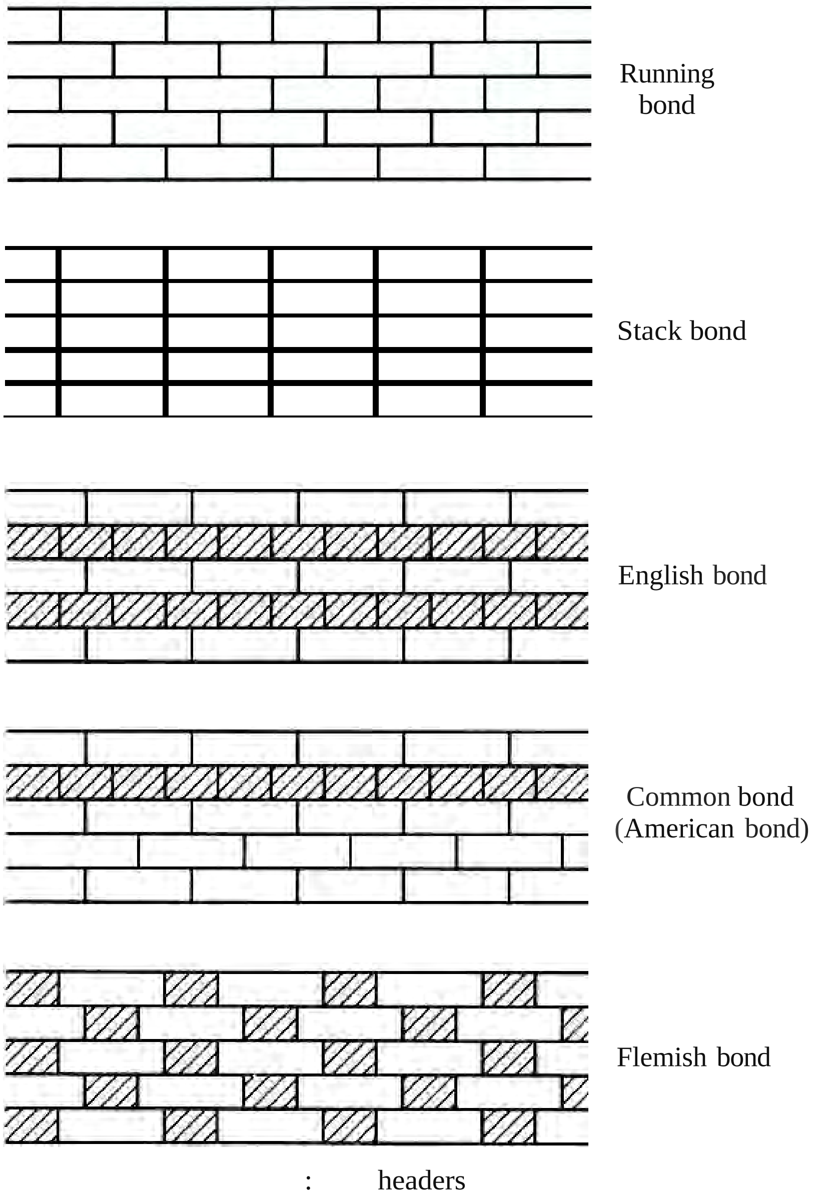


Figure 4.19 Types of masonry bonds.

The number of vertical joints in each course is the same. Flemish bond is more decorative and is not as strong as English bond.

A common bond or *American bond* consists of a course of headers for every few courses of stretchers. The number of courses of headers and stretchers varies from wall to wall, but it is more common to lay one course of headers for every four to seven courses of stretchers. The header course provides lateral strength to the wall.

Varied color bricks can be used in Flemish bond to give color-combination effects. Common bond is considered to be one of the strongest structural bonds because the header serves to bond the various wythes together. English bond provides exceptional strength across the width of the wall. The term *structural bond* refers to the system by which individual wythes are tied together or a single-wythe brick wall is tied to a backup. It involves laying header courses or the provision of metal ties in a cavity wall construction (Figs. 4.2c and 4.18). For a veneered wall over a framed wall, structural bond is provided by metal straps.

Rat-trap bond (also called *Chinese bond)* is a variation of Flemish bond. It has alternate headers and stretchers in each course, but the bricks are laid on edge instead of on a bed. This arrangement results in a cavity between the two wythes. This bond is cheaper than the other bonds but is less strong and is less weather resistant.

4.3.2 Types of Joint

In masonry construction individual masonry units are bonded together using head joints and bed joints (Fig. 4.5). Tight mortar joints are essential for good performance of walls. All joints-horizontal and vertical-must be filled to the depth of the face shell. A number of types of joints can be formed, as shown in Fig. 4.20, after the mortar is stiffened sufficiently.

The best weathertight joint is the *concave joint*, which is made with a special tool after the excess mortar has been removed with the trowel. *Flush joint* is made by keeping the trowel nearly parallel to the face of the wall while forcing the point of the trowel along the joint. It can also be done by rubbing the surface with a burlap sack. It is used when the wall is to be plastered or painted. *Raked joint* promotes leakage, and *concave*

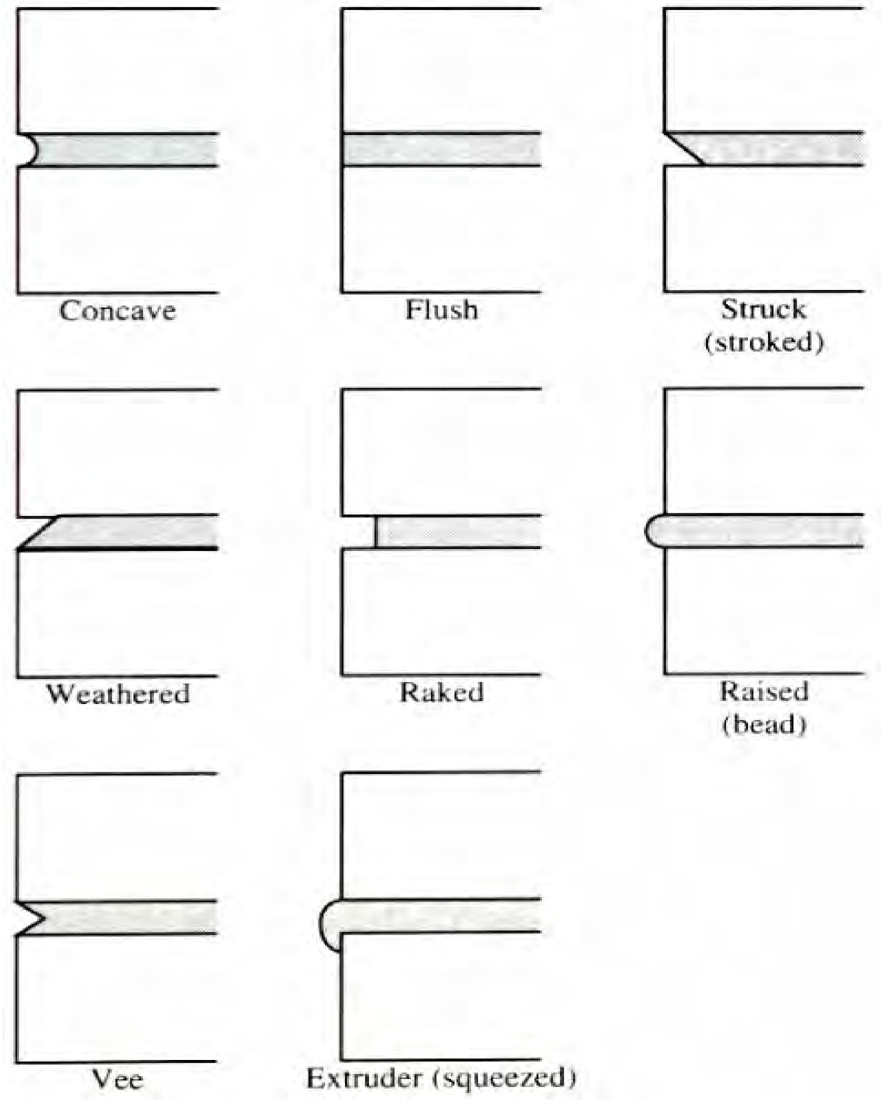


Figure 4.20 Types of joints.

and *vee joints* provide the best protection against leaks. Both these joints (concave and vee) produce stronger and more watertight bond.

Raked joints are made by removing the mort::ir with a tool while it is still wet, and *stripped joints* are made by placing wood strips in joints when the bricks are laid. Thin mortar joints produce stronger, watertight walls. When the thickness of joints exceeds ½ in. (12.5 mm), watertightness may be affected.

4.3.3 Control Joints and Expansion Joints

Concrete and brick masonry walls will undergo dimensional changes with changes in temperature and humidity. To provide for expansion and contraction and to force cracks at predetermined locations, control joints/expansion joints should be provided in masonry walls every 20 ft (6 m) or more in length. *Control joints* are used to curb movement in concrete masonry walls due to shrinkage resulting from loss of moisture and temperature changes.

Expansion joints control expansion of clay masonry due to absorption of moisture and temperature. Dimensions of a clay brick are the smallest after firing. **With** gain in moisture and with rise in temperature, the brick expands. Thjs increase in length is about 0.02% for each 1% increase in moisture, and is 0.03% per 100° F increase in temperature. If this expansion is prevented high compressive stresses will develop, causing crushing or displacement of bricks. In both these types of joints, tensile forces resulting from movements should be relieved to prevent cracking. This is accomplished by vertical control joints.

Control or expansion joint is a straight vertical joint from the top of the wall to its bottom built using half and full blocks (Fig. 4.21): All joints should be laid up in mortar joints as any other vertical joint (Figs. 4.22 and 4.23). Joints that are exposed to exterior environment should be sealed with a caulking compound. A recess can be provided for

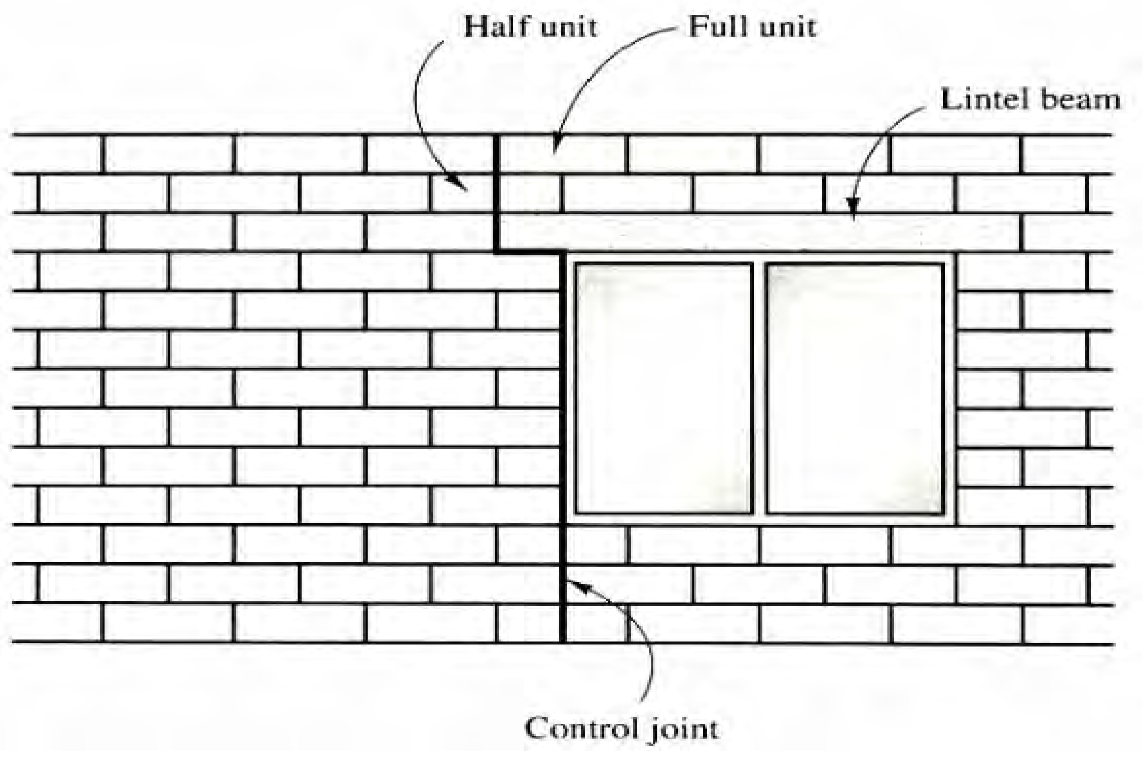


Figure 4.21 Vertical control joint.

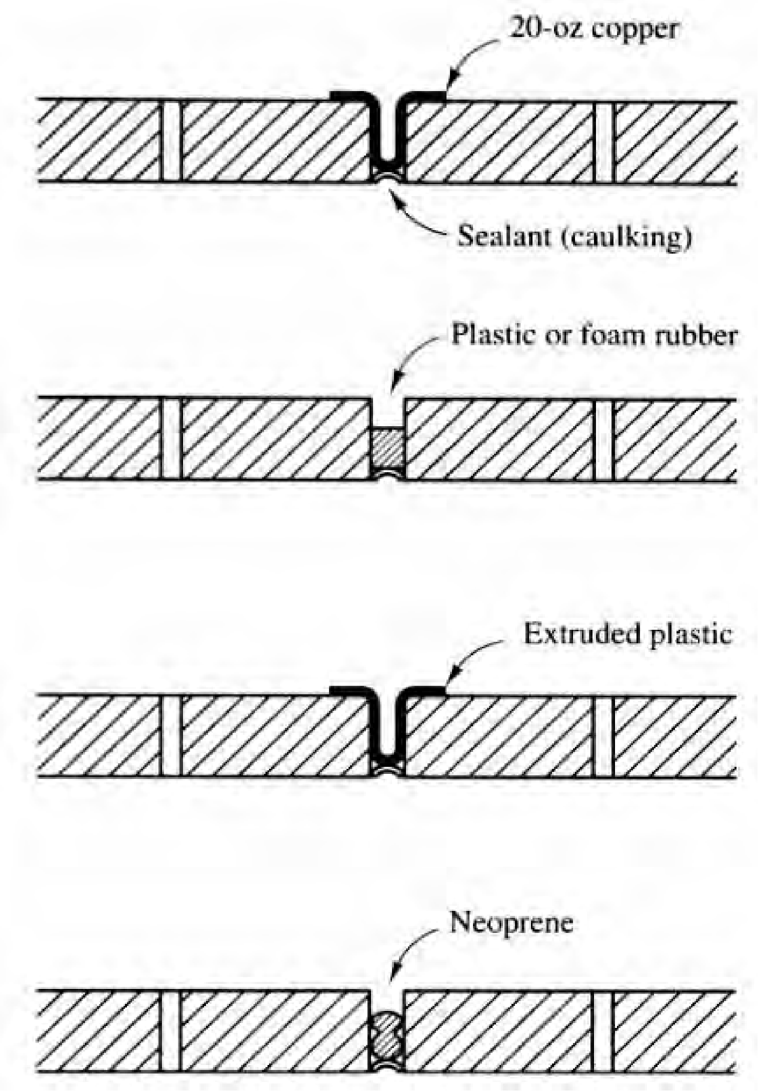


Figure 4.22 Expansion joints in brick-veneered wall.

the caulking material by raking out the mortar to a depth of about¾ in. (19 mm) after the mortar has hardened.

Concrete units, as they are made with cement, are known to shrink with time (drying shrinkage) and to creep when subjected to compressive loads. Clay units, on the other hand, absorb moisture from the environment and expand with time. The average coefficient of lineal thermal expansion for clay units varies between 2.5 and 4.0 x 10^{-6} in./°F. For concrete units this value depends on the aggregate type, and varies between 3.0 and 5.2 x 10^{-6} in./°F. Cinder aggregates has the lowest expansion coefficient; normal-weight aggregates have the highest.

Because concrete units are susceptible to shrinkage, it was indicated earlier that ASTM provides limits to the moisture content of type I units (Table 4.3). Note that type II units do not have to satisfy these limits. For concrete walls (unreinforced) using type I units the maximum spacing between control joints is two times the height of the wall or 40 ft, (12 m) whichever is smaller. In walls using type II units, this should be reduced in half.

Expansion joints in brick walls must be such as to permit relative movement due to thermal and moisture expansion. Spacing of these joints may vary between 32 and 150 ft (9.6 and 45 m). The width of the joint should be selected in such a way that it will at least close partially under any expansion and is limited to 1 in. (which permits 0.5-in. expansion of the wall). The width and spacing of expansion joints can be calculated using equations given at the end of this section.

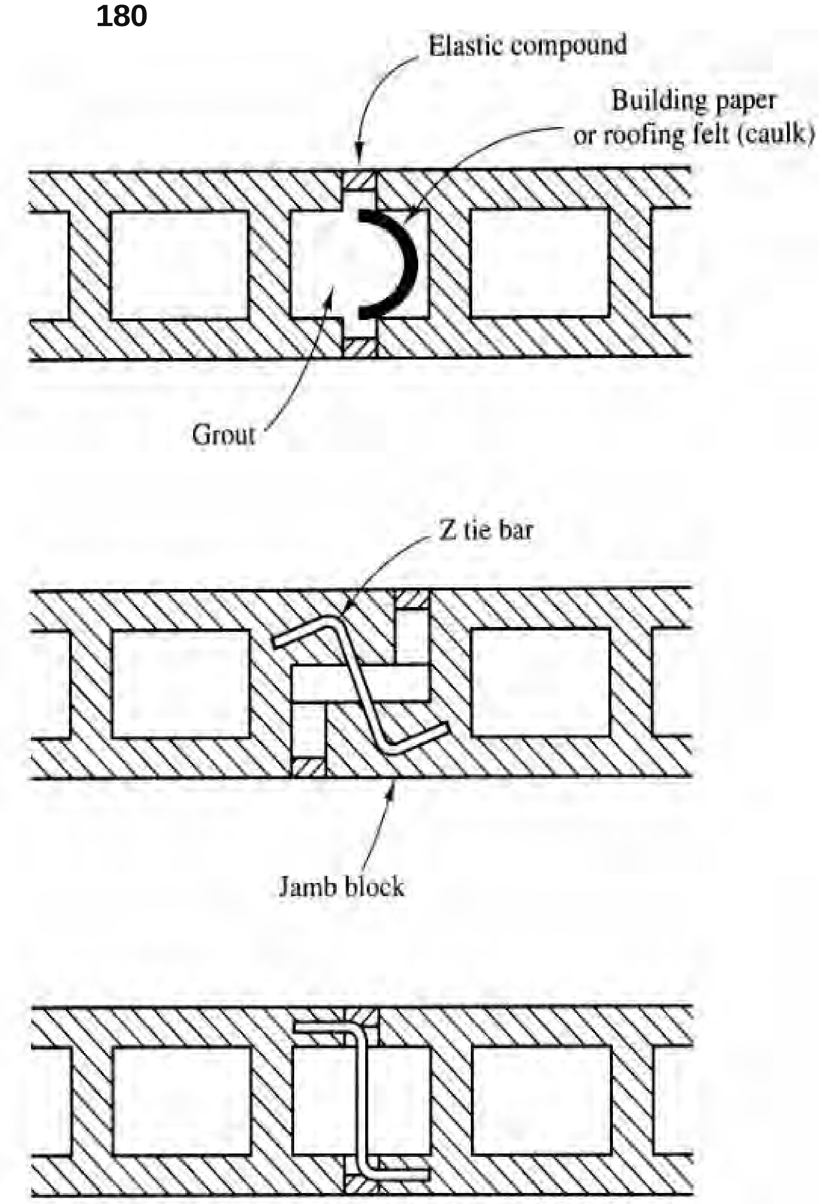


Figure 4.23 Control joints in block wall.

Lateral support for walls across the control joint can be provided using a number of techniques (Fig. 4.23). Use of control joint blocks at the joints provide lateral support. Placement of noncorroding metal Z tie bar 2 in. (5 cm) narrower than the width of the wall in every other horizontal joint ensures lateral support for wall sections on each side of the joint. Control joints can also be made with building paper or roofing felt inserted in the end core of the block, extending to the full height of the wall. The end core is then filled with grout to provide lateral support. The function of the building paper is to prevent mortar from bonding to one section of the masonry. Alternatively, control joint blocks, which look like tongue-and-groove-shaped blocks, can also be used to form control joints. At any type of vertical control joint, mortar is raked out to a depth of ¾in. (19 mm) before it hardens and is filled later with an elastic compound.

Control joints should also be provided when the wall thickness changes and at wall intersections (except corner walls). Intersecting concrete walls should not be tied together in a masonry bond except at the corners. Instead, one wall should terminate at the face of the other wall with a control joint at that joint. To provide lateral support for the intersecting walls, tie bars with two right-angle ends are embedded in joints and later grouted (Fig. 4.24). The tie bars are spaced at a maximum spacing of 4 ft (1.2 m) on

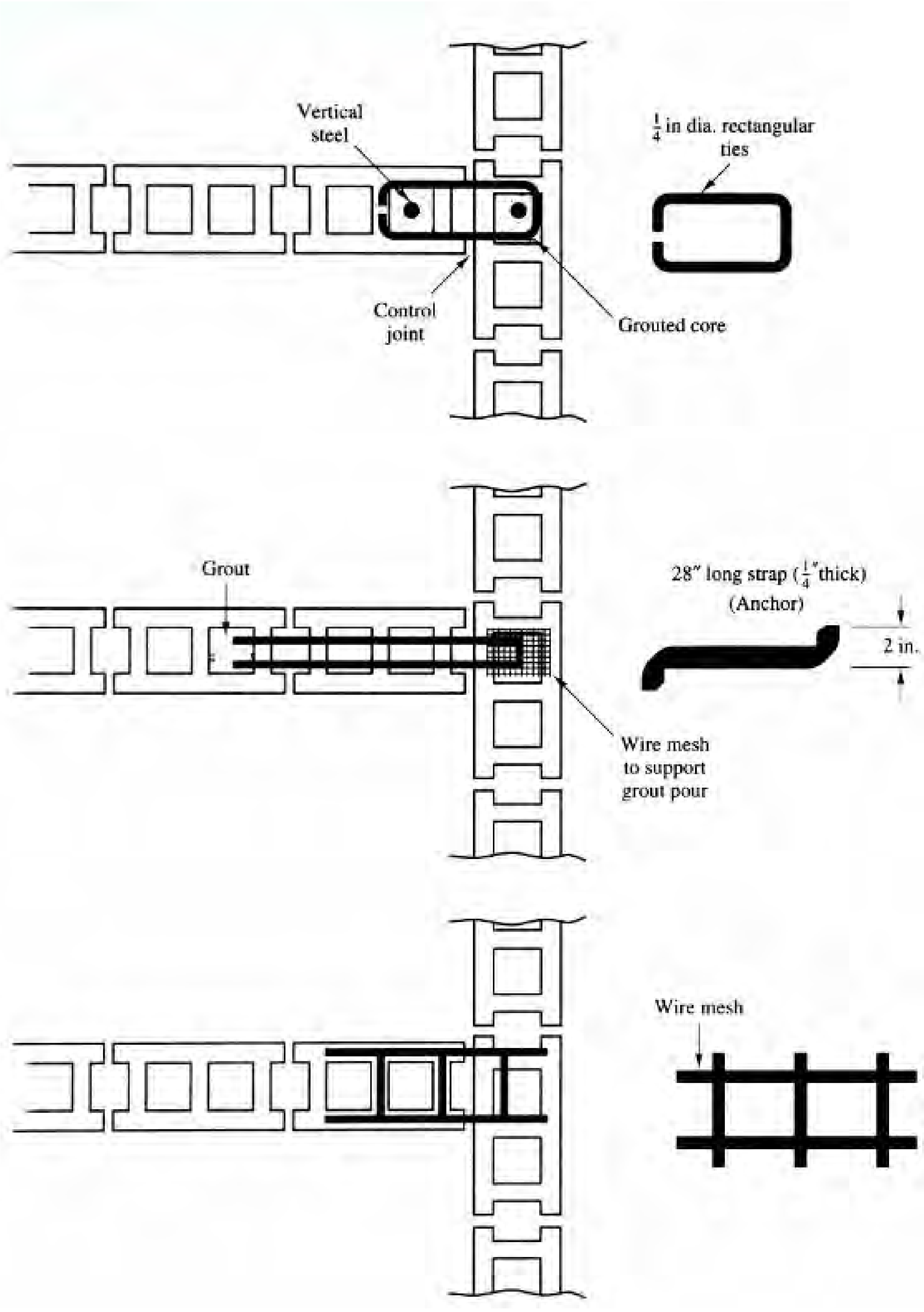

Vertical steel
$\frac{1}{4}$ in dia. rectangular ties
Control joint
Grouted core
Grout
28″ long strap ($\frac{1}{4}$″ thick) (Anchor)
2 in.
Wire mesh to support grout pour
Wire mesh

Figure 4.24 Control joints in intersecting walls.

centers vertically. Lateral supports can also be given using joint reinforcement (wire mesh), typically of No. 9 longitudinal wires.

In concrete masonry (unreinforced), the horizontal spacing of control joints (using type I units) is two times the height of the wall or 40 ft (12 m), whichever is smaller. For example, a wall of height IO ft will have a maximum spacing of control joints as the smaller of (a) 2 x 10 = 20 ft or (b) 40 ft. Thus the maximum spacing is 20 ft. With provision for reinforcement (reinforced masonry walls), this spacing can be increased.

For brick masonry the width and spacing of expansion joints can be estimated as

$$\text{net wall expansion} = [C_m + C_t(T_{max} - T_{min})]L$$

where C_m is the coefficient of moisture expansion, C_t the coefficient of thermal expansion; T_{max} the maximum mean wall temperature in °F, T_{min} in the minimum mean wall temperature in °F; L the length of wall in inches. Average values of C_m and C_t are 0.0002 and 0.0000040, respectively.

$$\text{Maximum spacing of expansion joints (feet)} = \frac{24{,}000\,(p)}{T_{max} - T_{min}}$$

where p is the ratio of opaque wall area to gross wall area. The spacing is generally between 150 and 200 ft (45 and 60m) for a straight length of wall. Expansion/control joints may also be located at sections of plan irregularity. Typically, they are located at pilasters, at changes in wall height and thickness, over openings, and at wall intersections.

4.4 PROPERTIES OF MASONRY

Important properties of masonry are:

- Density
- Compressive strength
- Flexural strength
- Modulus of elasticity
- Durability
- Thermal conductivity

Density or weight of a wall depends on weight of units, wall thickness, and grouting. As an example, the weight of 4-in.-thick (nominal) clay masonry wall is 37 psf (181 kglm^2). The weight of 8 in.-thick concrete masonry wall (unit height is 8 in.) is 58 psf using normal-weight units and 36 psf using lightweight units.

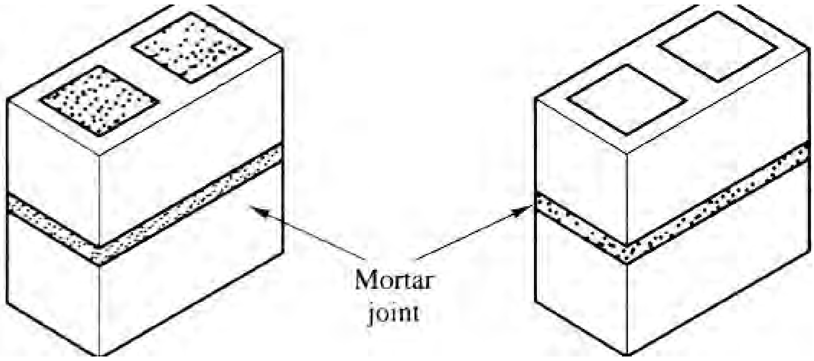
Compressive strength. Compressive strength of masonry depends primarily on the compressive strength of units, the mortar mix proportions, the amount of cement, grouting, and the workmanship and type of bond. An increase in cement content (of mortar) increases the masonry strength. The strength of masonry walls built with lime mortar may be about three-fourths to one-fourth of that built with cement mortar.

Studies have also shown that proportions of cement or lime can be altered without seriously affecting the strength of the masonry, although there is considerable variation in the compressive strength of the mortar. This means that the mortar strength has a limited effect on the compressive strength of the masonry. Consequently, strong mortars are not recommended in masonry construction. Moreover, high-strength mortars shrink tremendously, which weakens the bond. In addition, they may tend to exhibit a high rate of efflorescence.

The compressive strength of walls can be predicted most accurately from the strengths of masonry prisms constructed with similar material. Prisms contain two or more units bonded with mortar with or without grout, used primarily to predict the strength of the actual masonry wall (Fig. 4.25). The strength of the prism varies with its height; decreasing in strength with increase in height.

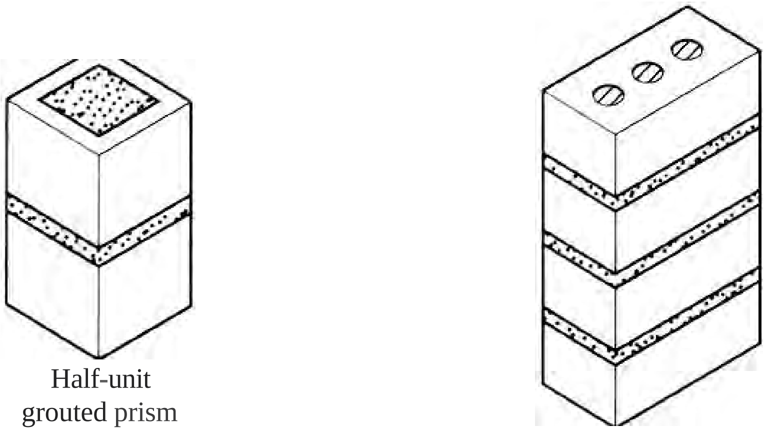
Testing of these masonry specimens in compression will provide the ultimate compressive strength, f_1 of the masonry. The allowable axial, flexural, shear, and bearing stresses in the wall are based on this compressive strength measurement.

When prism tests are not made, as is the case in most masonry construction, the compressive strength of masonry can be assumed from the values provided in the building codes (Fig. 4.26). They are listed for various compressive strengths of the units and mortar mixes. Their values range from a low of 875 psi (6 MPa) to a high of 2400 psi (16.6 MPa) for concrete units, and from 530 to 4600 psi (3.7 to 31.7 MPa) for clay units. Note that the compressive strength of concrete units may exceed 6000 psi (464 MPa) and



Grouted prism

Ungrouted prism



Half-unit grouted prism

Brick prism

Figure 4.25 Masonry prisms.

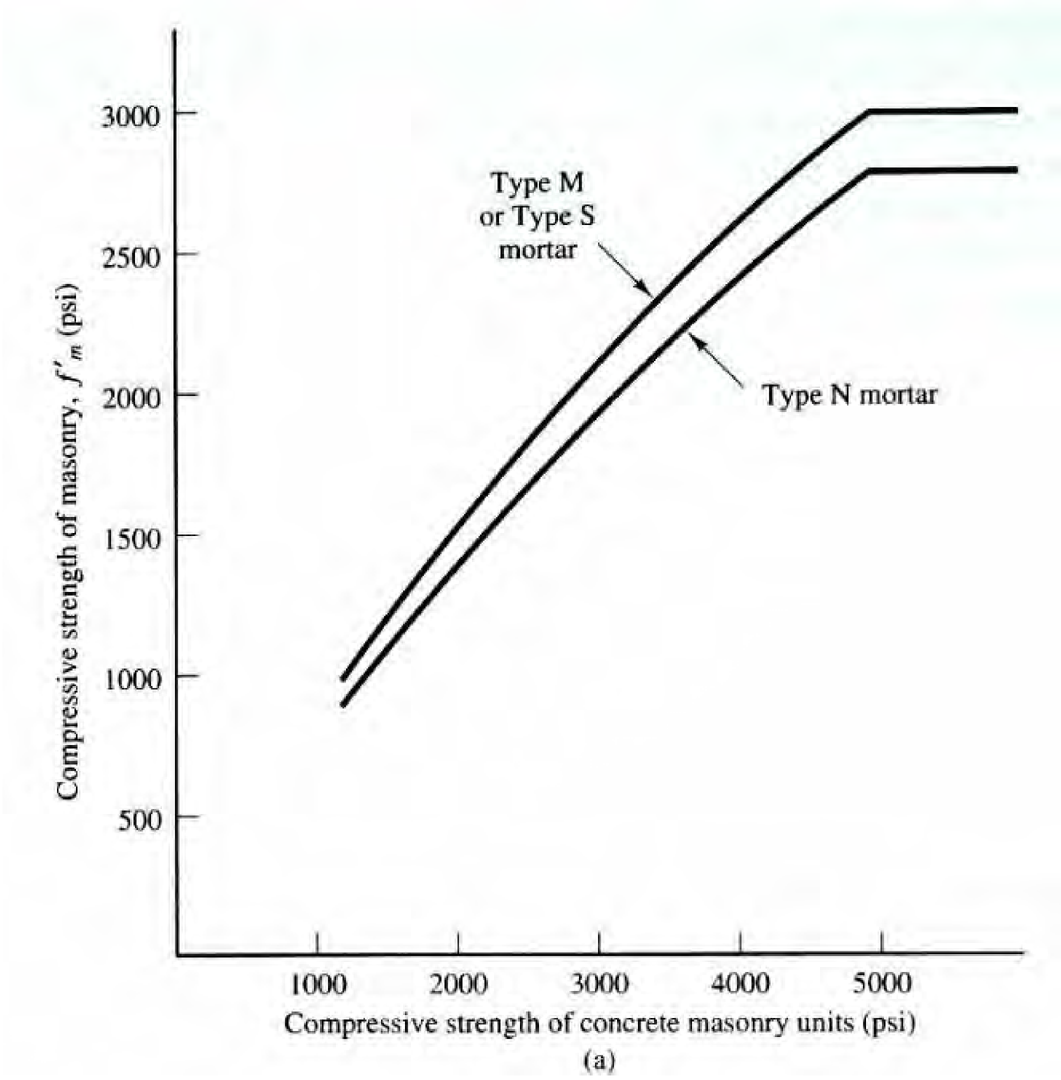


Figure 4.26a Compressive strengths of concrete masonry walls. (From UBC Table 24C. Reproduced from the 1991 edition of the *Uniform Building Code*, copyright© 1991, with the permission of the publisher, the International Conference of Building Officials.)

that of brick units can be as high as 14,000 psi (96.6 MPa). An increase in compressive strength of units does not necessarily correspond to a similar increase in the masonry strength due to weak mortar joints. For example, the compressive strength of brick masonry using 12,000 psi units and type S mortar is 2270 psi (in a model building code), whereas that of 6000-psi units and the same mortar is 1270 psi.

The allowable stresses in the masonry are calculated from the masonry compressive strength by applying a safety factor. The building codes allow higher allowable stresses when special inspection by a building official or engineer is provided during construction. This inspection is required during preparation of masonry wall prisms, sampling and placing of all masonry units, and placement of reinforcement. In addition, inspection is required of grout spaces, immediately prior to closing of cleanouts, and during all grouting operations. The allowable stresses for masonry constructed with special inspection is twice that in masonry without the special inspection.

Modulus of elasticity. There is no consistent relationship between ultimate compressive strength of wall and its modulus of elasticity. However most of the measured

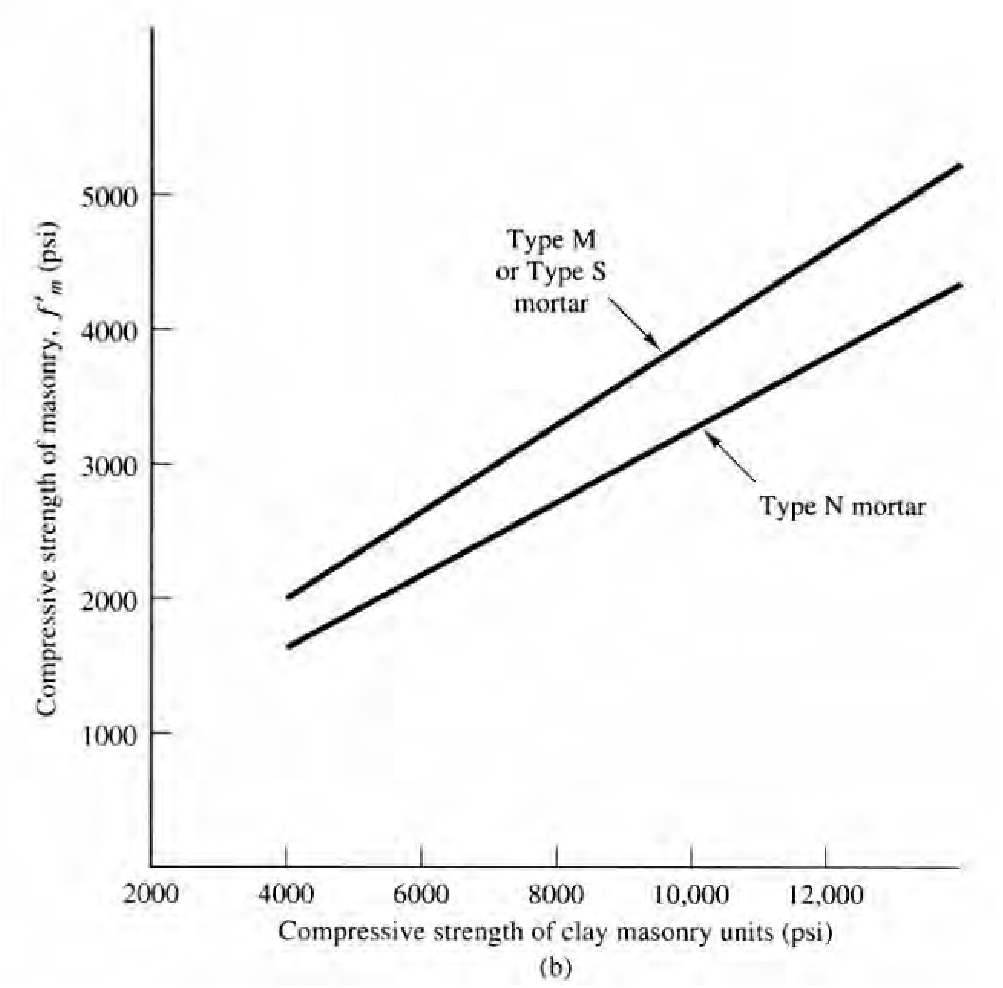


Figure 4.26b Compressive strengths of clay brick walls. (From UBC Table 24C. Reproduced from the 199I edition of the *Uniform Building Code,* copyright © 199I, with the permission of the publisher, the International Conference of Building Officials.)

£ values lie between 1200 and 700 times the compressive strength of the wall, as shown in Fig. 4.27. The modulus of elasticity values are affected by the wall design, the strength of the unit, the mortar strength, and the workmanship. When the workmanship remains the same, the modulus of elasticity increases with the brick strength and mortar strength and decreases with the increase in total thickness of mortar joints per unit length measured parallel to the direction of the compressive force.

Thermal conductivity. *Thermal conductivity* is defined as the time rate of heat flow through a unit area of a material from one surface to the other per unit temperature difference between the two surfaces. It is expressed in Btu (British thermal unit) per hour per square foot per degree Fahrenheit temperature gradient per inch of thickness. The thermal conductivity of masonry units depend on the density, the amount of moisture present, and the type of unit.

In general, thermal conductivity increases with the density and the amount of moisture content. Since air is a poor heat conductor, materials that are porous or contain a high proportion of air in their structure have low conductivity values. Conductivity of dense concrete is higher than that of common bricks, which is much higher than that of

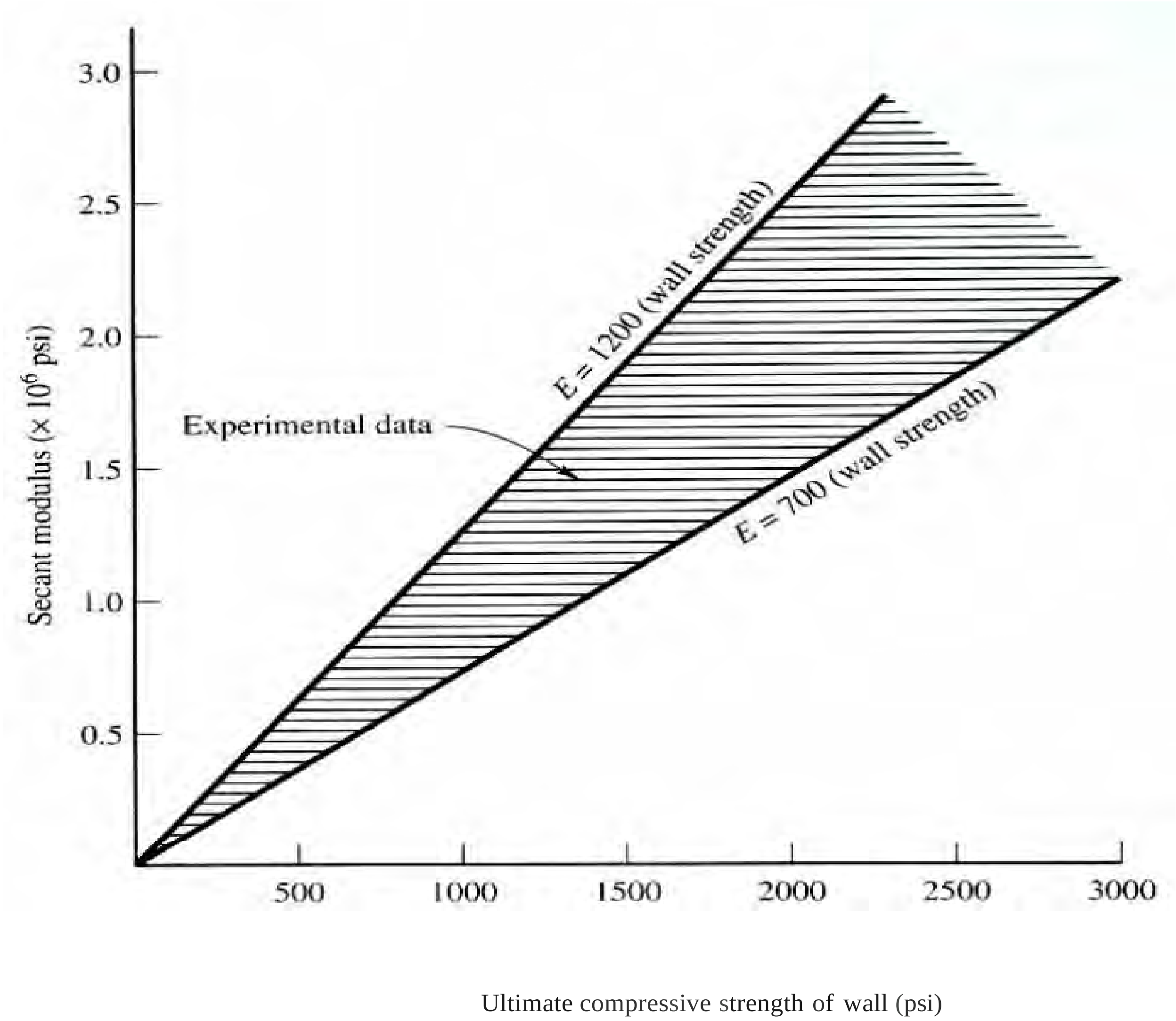


Figure 4.27 Relationship between modulus of elasticity and ultimate compressive strength of clay brick walls in cement-lime mortars.

fiberglass insulation. In double-wythe masonry walls, conductivity of outer wythe may be higher than that of inner wyther, due to a higher moisture content in the outer wythe.

Heat transfer. The heat transfer through a wall depends on the difference in temperature between the two sides. Through a wall containing voids the heat transfer takes place by convection, radiation, and conduction. *Convection* refers to the process whereby heat is transferred from one place to another by the movement and mixing of liquids or gases (e.g., convection ovens). *Radiation* is a process of transferring heat through invisible wave radiation similar to the transmission of light (e.g., solar radiation). *Conduction.* is a process in which heat is passed on between adjacent stationary particles of matter. From a microscopic standpoint, it refers to energy being handed down from one atom or molecule to the next one. Heat transfer through solid walls takes place only by conduction.

The overall transmission of heat from the air on one side of a structure to the air on the other side is defined as the *heat transmission coefficient* (or *overall coefficient of heat transmission* or *thermal transmittance).* Called the *U-value* of the structure, it is related to the conductivity of the material. Note that the heat transmission coefficient has the same unit as the conductivity, with the exception that the former refers to the thickness of the material.

The U-value is measured in Btu per hour per square foot per degree Fahrenheit difference in temperature between the air on the warm and cool sides of the wall. One Btu (British thermal unit) is the heat required to raise the temperature of 1 pound of water 1 degree Fahrenheit at sea level. Brick cavity walls have U-values in the range 0.25 to 0.35, and solid walls have U-values of 0.3 to 0.5; the lower the U-value, the thicker the wall. Plastering the wall decreases the U-value and so does insulation. Lightweight hollow concrete wall has a *V* value of about 0.33. The U-value of a wall can be calculated by knowing the thermal conductivities of all materials through the thickness of the wall.

The U-values indicated above assume a constant differential temperature between the air on the inside and the outside and do not take into account the daily cycles of solar radiation. air temperature. and air velocity. These causes result in temperature fluctuations that produce a dynamic thermal response which can differ substantially from heat flow calculations based on standard U-values.

The massive masonry walls in many older buildings are more thermally stable than the modern lightweight walls. A solid masonry wall is heavy enough to store heat and retard its migration substantially. This characteristic, called *thermal storage capacity,* is a measure of the quantity of heat required to raise the temperature of a mass of the material. Two materials may have the same U-values or insulating values, but the heavier wall requires longer to heat up than does the lighter wall. Similarly, the lighter wall will cool down faster than the heavier wall. Partition walls of high thermal storage capacity are capable of storing more heat during the night than are lightweight partition walls.

4.4.1 Efflorescence

Clay bricks contain soluble salts that migrate to the surface with water. As water evaporates to outside air, these salts will collect on the face of brickwork as patches of white crystals. These irregular and unsightly patches are called *efflorescence* (meaning "powdery substance").

The most common salts are calcium and magnesium sulfates, although various salts of potassium and sodium are also found. The percent of calcium sulfate in bricks is generally very high compared to the other salts. These salts generally originate from the raw clay or in some cases are formed in the burning process. Aggregates washed by seawater may contain sodium chloride and other salts that contribute to efflorescence. Some curing compounds and air-entraining admixtures may contain sodium chloride or calcium chloride solution, which accelerates the efflorescence.

The amount of efflorescence depends on the type and amount of salts. Some salts, such as calcium sulfate, are less soluble and take a longer time to leach out of bricks. The solubility of magnesium sulfate is greater and may cause flaking of the brick faces. This is the most destructive soluble salts in clay units.

Efflorescence is usually white in color. it occurs more often in winter and following heavy rains. In coastal areas, efflorescence may be caused by sea salts. Note that without water or moisture in the wall, there will be no efflorescence. Cyclic changes in moisture-alternate wetting and drying cycles-contribute great y to efflorescence.

The efflorescence is more pronounced in exposed walls such as parapets, chimneys, and basement walls. These white salts do not cause damage or deterioration but result in a unsightly surface. To prevent efflorescence, the wall must be protected from water migration. Any method to prevent water migration into the wall is helpful in controlling efflorescence. Bricks that have been saturated before they are laid are more prone to efflorescence than are those laid surface-wet. The units must be free of soluble salts. The construction should allow for the drainage of rainwater away from the walls. The exterior walls can be capped and flashings may be needed to keep rainwater away from the outside face of the wall.

4.5 REINFORCED MASONRY

Reinforced masonry is that form of masonry construction in which reinforcement acting in conjunction with the masonry is used to develop flexural strength and resist lateral loads. *Reinforced grouted masonry* is that form of construction made with solid clay units (bricks) or solid concrete building brick in which interior spaces of masonry are filled by pouring grout around reinforcement therein (Fig. 4.28). The minimum grout space (space between wythes) is 2½ in. (6.3 cm) for low-lift grouted construction, and generally does not exceed 5 in. (12.5 cm). The thickness of the grout between bricks and reinforcement (cover) should be equal to or greater than one bar diameter. In high-lift grouted construction, the two wythes must be bonded together with wall ties (minimum No. 9 wire) spaced at a maximum of24 in.(61cm)horizontally and 16 in. (40 cm) vertically (for running bond construction). Cleanouts are required. The grout space must be a minimum of 3½in. (9 cm).

Reinforced hollow unit masonry is that type of construction made with hollow masonry units in which cells are continuously filled with grout and in which reinforcement

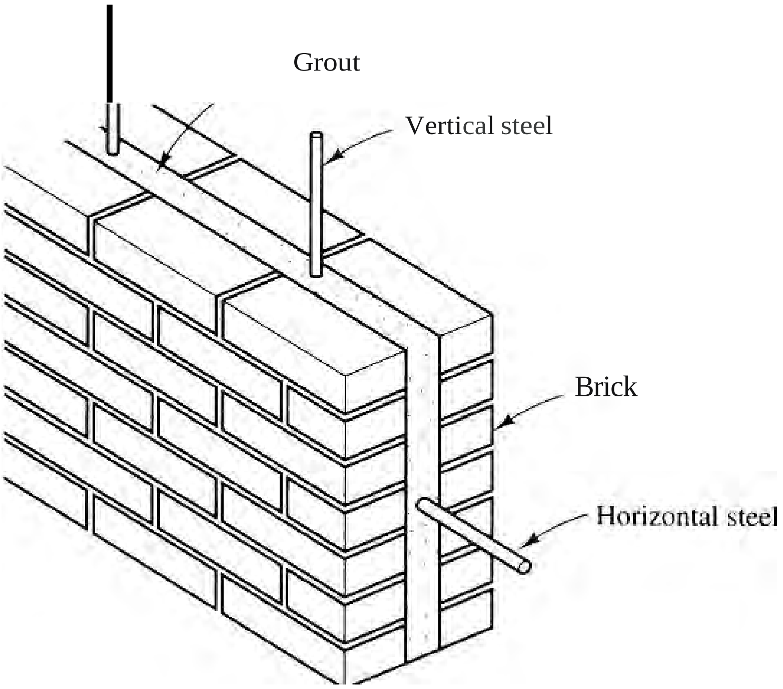


Figure 4.28 Reinforced brick wall (reinforced grouted masonry).

is embedded (Fig. 4.29). Generally, all cells are filled with grout. The method of construction can be low-lift or high-lift. In the former the maximum height of construction laid before grouting is 2 ft, (0.6 m) whereas in the latter, the full height of construction between horizontal cold joints is grouted in one operation. Note that all reinforcement, horizontal and vertical, must be embedded in the grout. The horizontal reinforcement is placed on bond beam units with a minimum grout cover of 1 in. (2.5 cm) above steel for each grout pour. In the high-lift method of construction, cleanouts are required.

The design of these walls should conform to the relevant specifications of building codes. Masonry is assumed to carry no tensile stresses, and reinforcement is assumed to be completely bonded to the masonry. Reinforced masonry construction is used for load-bearing walls, retaining walls, columns, and beams.

4.6 MIX PROPORTIONING AND EXAMPLES

The amount of mortar required in a masonry wall can be calculated by knowing the size of the units and the thickness of the joints. Using modular bricks of nominal size: 2½ x 4 x 8 in. and ¾-in. joints, the approximate quantity of mortar required per 100 ft^2 of wall area is about 6 ft^3. Increase in the thickness of joints to ½ in. will increase this

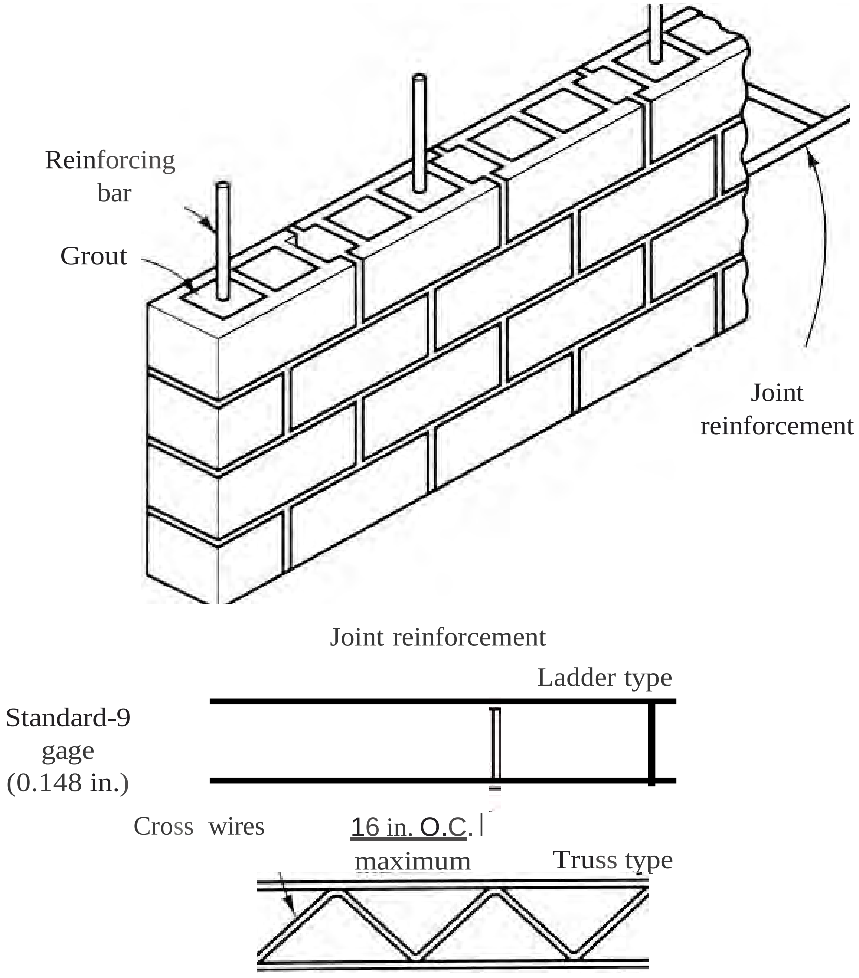


Figure 4.29 Reinforced hollow unit masonry.

quantity by about 30%. The number of bricks required for the wall can be calculated by knowing the dimensions of brick.

Example4.1

Find the number of clay bricks required for a wall of height 10 ft and length 25 ft. Use modular bricks of size: 4 X 2½ X 8 in.

Solution

Surface area of bricks = height X length

= **2½X8 =2l.3in.^{2}**

= 0.148 ft^2

Number of bricks per I00 ft^2 of wall area = $\dfrac{100}{0.148}$ =676

Provide 5% allowance for wastage.

Total number of bricks = 710 per 100 ft^2

Area of wall = 25 X 10 = 250 ft^2

Number of bricks required for wall = $\dfrac{710}{100}$ X 250

= 1775

The amount of ingredients required for mortar can be calculated by knowing the mix proportions. Mortar can be mixed by weight or volume. Proportioning by weight is more accurate (due primarily to bulking of sand when moist, which results in incorrect volume measurement), but mortar is generally proportioned by volume. It is estimated that I ft^3 of damp loose sand will yield about 1 ft^3 of mortar. Note that 1 loose cubic foot of cement and lime weighs 94 lb, and 40 lb respectively. The specific gravities of cement and lime are 3.15 and 2.25, respectively.

Example 4.2

Using type S mortar, determine the quantities of ingredients to mix I00 ft^3 of mortar.

Solution From Table 4.6, for type S mortar, determine the mix proportions. Let

volume of cement = V_C cubic feet

volume of lime, V_1 = ¼ to ½ of V_C

volume of sand, Vs = 2¼ to 3 times (V_C+V_1)

= 2.81 to 4.5 times V_C

Use the following mix proportions:

Volume of cement = V_c

Volume of lime = $0.5V_C$

Volume of sand = $4.5V_C$

Assuming a yield of I ft^3 of mortar for 1 ft^3 of damp loose sand, for 1 ft^3 of mortar,

$$V_s = \text{I ft}^3$$

$$V_c = \frac{1}{4.5} = 0.222\ \text{ft}^3$$

$$V_l = \frac{0.5}{4.5} = 0.111\ \text{ft}^3$$

For 100 ft^3 of mortar,

$$V_s = 100\ \text{ft}^3$$

$$V_c = 22.2\ \text{ft}^3$$

$$V_l = 11.\text{I ft}^3$$

The weights of ingredients can also be determined from mix design based on weight. The unit weight of sand in a moist loose condition is taken as 80 pcf. For **1** ft^3 of mortar,

Weight of sand = 80 lb

Weight of cement = (94 lb/ft^3 of loose volume)

= 0.222(94) = 21 lb

Weight of lime (I ft^3 of lime weighs 40 lb) = 0.111(40) = 4.44 lb

Example 4.3

Find the absolute volume of all materials in Example 4.2. Assume a water/cement ratio of 0.7 by weight (about 1½ gal per cubic foot of mortar). Specific gravity of sand = 2.65. Moisture content of sand= 7%. Air content= 6%.

Solution

$$\text{Absolute volume of cement} = \frac{21}{3.15(62.4)} = 0.11\ \text{ft}^3$$

$$\text{Absolute volume of lime} = \frac{4.44}{2.25(62.4)} = 0.032\ \text{ft}^3$$

$$\text{Dry weight of sand} = \left(1 - \frac{2}{100}\right) \times 80 = 74.4\ \text{lb}$$

$$\text{Volume of sand} = \frac{74.4}{2.65(62.4)} = 0.45\ \text{ft}^3$$

$$\text{Water in sand} = \left(\frac{7}{100}\right) * 80 = 5.6\ \text{lb}$$

$$\begin{aligned}
\text{Mixing water} &= 0.7(21)\\
&= 14.7\ \text{lb}\\
\text{Total water} &= 20.3\ \text{lb}\\
\text{Volume of water} &= \frac{20.3}{62.4}\\
&= 0.33\ \text{ft}^3\\
\text{Total volume of ingredients} &= 0.11 + 0.032 + 0.45 + 0.33\\
&= 0.922\ \text{ft}^3\\
\text{With 7\% air, net volume of mortar} &= \frac{0.922}{0.93}\\
&= 0.99\ \text{ft}^3\\
&= \mathbf{1\ ft^3}
\end{aligned}$$

Note that I ft^3 of sand yields about 1 ft^3 of mortar.

4.7 TESTING

A number of laboratory tests are described in this section. Following is a list of masonry properties and the corresponding test numbers.

PROPERTY	TEST NO.
Absorption of bricks	MAS-3, MAS-4
Saturation coefficient of bricks	MAS-4
Suction of bricks	MAS-5
Compressive strength of bricks	MAS-2
Modulus of rupture of bricks	MAS-1
Mortar flow	MAS-6
Compressive strength of mortar cubes	MAS-7
Compressive strength of concrete masonry prisms	MAS-8

Test MAS-1: Modulus of Rupture of Brick

Purpose: To calculate the bending strength of clay brick specimens.

Related standards: ASTM C67.

Definition:

- *Modulus of rupture* is the tensile strength of brick determined from a flexural test.

Equipment: Balance, universal testing machine steel bearing plate (1½ in. wide and ¼ in. thick drying oven.

Sample: Full-sized dry unit. The unit is dried at 230° F (110° C) for 24 h, and cooled for 4 h.

Procedure:

1. Measure the average cross-sectional dimensions.
2. Support the specimen flatwise (load is applied in the direction of the depth of the unit).
3. The span length is 1 in. less than the basic unit length.
4. The specimen is loaded at the midspan.
5. Apply the load to the upper surface through the steel bearing plate.
6. The end supports should be able to rotate.
7. Apply the load at a rate of 0.05 in. (1.27 mm) per minute (crosshead movement).
8. Using the maximum load, calculate the value of **MOR.**

$$\text{MOR} = \frac{3WL}{2bd^2} \quad \text{psi}$$

where, W is the maximum load in pounds, L the span length in inches, b the average overall width in inches, and d the average overall depth in inches.

Report: Report the average MOR value.

Test MAS-2: Compressive Strength of Brick

Purpose: To determine the compressive strength of brick samples.

Related standard: ASTM C67.

Equipment: Universal testing machine; drying oven; capping pot and mold.

Sample: Half-size dry unit (dried and cooled as in Test No. MAS-1). The length of the specimen is one-half the full length of the unit.

Procedure:

1. Measure the dimensions at the top and bottom of the specimen.
2. Cap the specimen with sulfur (thickness of cap is about¼in.).
3. Allow the cap to cool for a minimum of 2 h.
4. Test the specimen flatwise (load is applied in the direction of the depth of the brick).

5. Apply the load continuously so that the failure takes place within 2 to 3 min.
6. Calculate the compressive strength as:

$$\text{compressive strength} = \frac{W}{A}$$

where Wis the maximum load and A is the average of the gross areas of the upper and lower bearing surfaces of the specimen.

Report: Report the average compressive strength.

Test MAS-3: 24-Hour Absorption of Brick

Purpose: To determine the amount of absorption of brick by immersion for 24 **b.**

Related standard: **ASTM** C67.

Definition:

- *Absorption* is the weight of water absorbed after 24 h of submersion in cold water expressed as a percent of the dry weight of the brick.

Equipment: Drying oven, balance, pan or container.

Sample: Half-brick specimen dried and cooled as in Test MAS-1.

Procedure:

1. Obtain the dry weight of the specimen, W_d.
2. Submerge the specimen in clear water for 24 h.
3. Remove the specimen at the end of 24 h.
4. Wipe off the surface water with a damp cloth and weigh, W_s.
5. Calculate absorption as

$$\text{absorption} = \frac{W_s - W_d}{W_d} \times I00$$

Report: Report the absorption of a11 specimens (percent).

Test MAS-4: Absorption by 5-Hour Boiling and Saturation Coefficient

Purpose: To determine the absorption of brick samples by the 5-h boiling method and calculate the saturation coefficient.

Related standard: ASTM C67.

Definition:

- *Saturation coefficient* is the ratio between absorption after 24 h in cold water and absorption after boiling for 5 h.

Equipment: Balance, container.

Sample: Use the saturated half-brick specimen from Test MAS-3.

Procedure:

1. Submerge the specimen in clear water at 60 to 86° F (15.5 to 30° C). Note that water has to circulate on all sides of the specimen.
2. Heat the water to boiling and continue boiling for 5 h.
3. Allow it to cool by natural loss of heat.
4. Remove the specimen, wipe off the surface water with a damp cloth, and weigh, *Wb*.
5. Calculate the absorption as

$$\text{absorption} = \frac{Wb - Wd}{Wd} \times 100$$

$$\text{saturation coefficient} = \frac{Ws - Wd}{Wb - Wd}$$

Note that *Ws* and *Wd* are obtained in Test MAS-3.

Report: Report the percent of 5-h absorption and saturation coefficient values.

Test MAS-5: Initial Rate of Absorption (Suction) of Bricks

Purpose: To calculate the initial rate of absorption of brick units.

Related standard: **ASTM** C67.

Definition:

- *The initial rate of absorption* is the amount of water absorbed by a standard brick (of surface area 30 in^2) after I min in ¼in.of deep water.

Equipment: Balance, container (tray), ¼-in^2 6-in.-long noncorrodable metal bars-two required (aluminum).

Sample: Whole-brick specimen, dried and cooled as in Test MAS-1.

Procedure:

1. Measure the length, *L* (in.), and width, *B* (in.), of the specimen.
2. Weigh the specimen, *Wd* (g).

3. Set the two metal bar supports in the tray.
4. Add water in the tray so that the depth of the water is ½ in. above the bottom of the test brick.
5. Set the test brick in place flatwise on metal supports without splashing.
6. Remove the brick at the end of 1 min.
7. Wipe off the surface water with a damp cloth and weigh, '''.r (g).
8. Calculate the initial rate of absorption as

$$\text{Initial rate of absorption} = \frac{30(W_s - W_d)}{L\ (B)}$$

Report: Report the average initial rate of absorption in g/min.

Test MAS-6: Determination of Mortar Flow

Purpose: To calculate the flow of mortar samples.

Related standards: ASTM C109, C230.

Definition:

- *Flow* is the increase in the average diameter of the mortar mass in the flow table expressed as a percentage of the original base diameter.

Equipment: Flow table, flow mold, standard tamper (½ x I x 6 in. size, rubber or oak), trowel.

Sample: Mortar sample of desired mix proportions.

Procedure:

1. Wipe the flow table top clean and dry.
2. Place the flow mold at the center of the table.
3. Place a layer of mortar about 1 in. (25 mm) in thickness and tamp 20 times with the tamper.
4. Fill the mold to the top and tamp 20 times.
5. Cut off the mortar to a plane surface, flush with the top of the mold using a trowel.
6. Wipe the table top clean and dry.
7. Lift the mold away from the mortar 1 min after completing the mixing operation.
8. Immediately drop the table through a height of ½ in. (12.7 mm) 25 times in 15 s.
9. Measure the diameter along four places.
10. Using the average base diameter, calculate the flow.

$$\text{Flow} = \frac{\text{increase in average diameter}}{4} \quad 100$$

11. Continue varying the water content in the mix until the desired flow is obtained.

Report: Report the amount of water (water/cement ratio) required for the desired flow.

Test MAS-7: Compressive Strength of Mortar Cubes

Purpose: To determine the compressive strength of mortar of known mix proportions using 2-in. (50-mm) cube specimens.

Related standard: ASTM C109.

Equipment: Cube molds, universal testing machine, tamper (Test MAS-6), mixer or mixing bowl, trowel.

Sample: Use mortar from Test MAS-6. (If no mix proportions are given, use 500 g of cement, 1375 g of sand, and an initial water of 220 g. Increase the amount of water until the desired flow is obtained. The quantity of ingredients will make six cubes.)

Procedure:

1. Apply a thin layer of mineral oil to inside surface of the mold.
2. Remove the excess oil with paper towel.
3. After mixing the mortar fill the mold with mortar for a depth of about 1 m. (25 mm).
4. Tamp the mortar in all the cube compartments 32 times in about 10 s in four rounds, each round to be at right angles to the others.
5. Fill the compartments with the remaining mortar and tamp as specified in the first layer.
6. Smooth off the cubes by drawing the flat side of the trowel (with the leading edge slightly raised).
7. Cut off the mortar to a plane surface flush with the top of the mold by drawing the straight edge of the trowel.
8. Store the specimens covered with a plastic sheet at room temperature for 24 h.
9. Transfer the specimens in the mold to the moist room.
10. Remove the specimens in the mold from the moist room. Remove the specimens from the mold.
11. Transfer the specimens to the moist room and keep them up to the testing age (7 or 28 days).
12. Test them immediately after removal from the moist room. Wipe the specimens to a surface-dry condition.

13. Apply the load to the specimen faces that were in contact with the true plane surfaces of the mold.
14. Loading rate should be such that the maximum load will be reached at about 30 s to 1½ min.
15. Determine the compressive strength as

$$\text{compressive strength} = \frac{\text{maximum load}}{4} \quad \text{psi}$$

Report: Report the compressive strength of all specimens and the average. Value.

Test MAS-8: Compressive Strength of Concrete Masonry Prisms (Hollow)

Purpose: To calculate the compressive strength of masonry using concrete hollow blocks and known mortar.

Related standard: ASTM E447.

Definition:

- A *masonry prism* is an assemblage of masonry units, mortar, and sometimes grout used as a test specimen for determining properties of the masonry.

Equipment: Universal testing machine, capping mold and pot, trowel.

Sample: Use half-blocks (length = width = 8 in.) to build a prism of nominal height = 16 in. Fully bed the face shells with mortar. Strike mortar joints flush with the face of the masonry without tooling.

Procedure:

1. Cure the specimens for 28 days in *moist* room.
2. Take the specimens out of the *moist* room and measure the average cross-sectional dimensions.
3. Cap the specimens as in Test MAS-2.
4. Apply the load at a uniform rate so that the maximum load is reached in 1 to 3 min.
5. Note the loading at which the first cracking sounds are heard.
6. Note *(if* observed) the load corresponding to the first crack.
7. Note the maximum load.

Report: Describe the mode of failure. Determine the compressive strength based on net area.

CHAPTER 5

Wood and Wood Products

Wood is one of the oldest known materials of construction, and it is the only naturally renewable building material. A number of factors, such as simplicity in fabrication, lightness, reusability, and environmental compatibility, have made this material one of the most popular in light construction. Although many construction products using wood as the raw material have been introduced into the construction market in the last 20 or more years and are presently being used extensively, the dominant use of wood is still in the form of lumber-pieces of wood cut from tree trunks. Mature trees, primarily those having evergreen needlelike leaves, are the source of structural timber; the trunk, when cut, represents a *log* from which timber is sawed.

In this chapter we look at the structure of trees, manufacture of lumber, grading of lumber and wood products, properties of wood, and application of wood and wood products. Although a lot of generalizations are made in the following pages, it should be understood that the physical and mechanical properties of wood vary tremendously even within a tree.

A cross section of a log or trunk is shown in Fig. 5.1. It is surrounded by a rough and dense covering called *bark*. Inside the bark there exists a thin layer of wood cells called *cambium,* in which the growth of wood takes place continuously. This growth eventually results in a ringlike structure referred to as *annual ring* (or *annular ring* or *growth ring).* Rapidly growing trees having wide annual rings produce coarse-grained wood, whereas slow-growing trees having narrower annual rings produce fine-grained

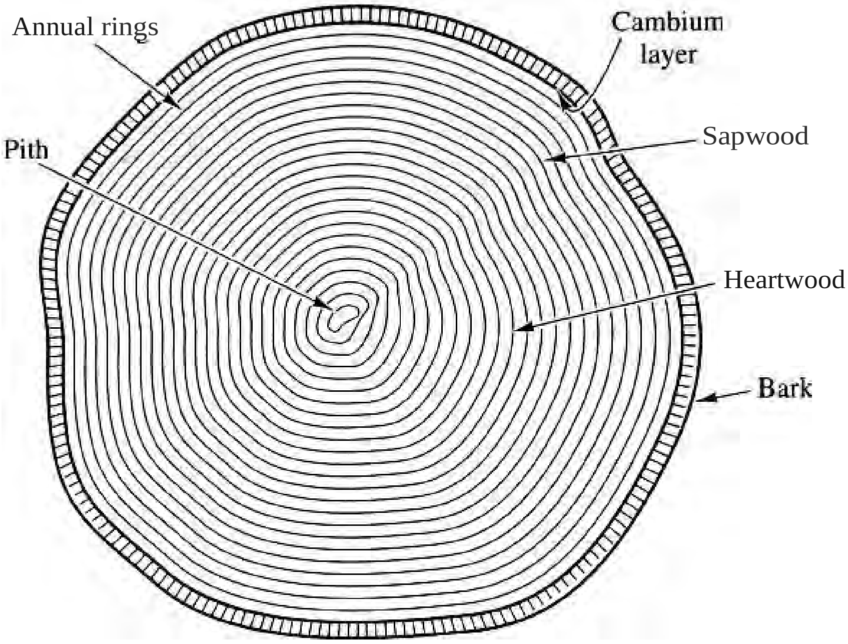


Figure 5.1 Section through a log.

wood. *Wood grain* refers to the arrangement of wood fibers. Although growth rings are found in the trunks of most hardwood and softwood species, trees such as palm and coconut do not possess a ringlike structure.

The center of the log, called *pith,* is surrounded by the annual rings, the number of which represents the approximate age of the tree. A tree with 250 annual rings is roughly 250 years old. A number of Redwood trees in northern California are more than 2500 years old.

In most species each annual ring appears to have two layers: an inner layer and an outer layer. The inner layer of each ring represents the more rapid spring growth and is referred to as *springwood* or *early wood.* The outer layer, on the other hand, represents a heavier, harder, stronger material called *summerwood.* The proportion of summerwood to springwood affects the density of wood, which in turn affects its strength.

In each tree the inner part of the trunk is made up of dead tissues (or cells), and the primary function of this part is to provide mechanical support to the tree. This part of the log, called *heartwood,* is darker, drier, and harder than the outer part, known as *sapwood.* Although the differences in density and strength between the heartwood and the sapwood are very small, the sapwood is less durable and more permeable (which means that impregnation with preservatives is easier) than heartwood.

Wood is broadly classified into two categories:

- Hardwood (deciduous trees)
- Softwood (conifers)

Hardwood is any tree that has broad leaves which are shed in winter, whereas *softwood* is any species that has needlelike leaves and is generally evergreen. Oak, Maple, and Ash are examples of hardwoods, and Douglas Fir, Larch, Pine, and Redwood are examples of softwoods. Table 5.1 lists some common softwood and hardwood species. The terms

TABLE 5.1 COMMON SOFTWOODS AND HARDWOODS

Softwoods	Hardwoods
Douglas Fir	Ash
White Fir	Basswood
Western Hemlock	Cottonwood
Western Larch	Aspen
Ponderosa Pine	Birch
Western White Pine	Elm
Redwood	Red Oak
Sitka Spruce	Black Walnut
Balsam Fir	Maple
Eastern Hemlock	White Oak
Eastern White Pine	
Eastern Red Cedar	
Southern Pine	

hardwood and *softwood* do not necessarily indicate the relative hardness or density between the two categories, although it is true that most hardwoods are harder to work with than most softwoods. Conifers are easier and faster to grow, which makes them cheaper than hardwoods, and accordingly, most of the structural lumber used in North America is derived from the softwood category.

Wood differs from species to species and also within each species. The conditions of growth, such as climate, density of the surrounding forest, character of the soil, the location where the lumber is derived from the log, moisture content, and defects influence the mechanical properties of wood of a given species.

In an attempt to simplify the structural design process and limit the large number of variables that affect the properties of wood, the available species are divided into groups of species. A *group of species* will include one or more species that have very similar characteristics and mechanical properties. For example, the species group Eastern Softwoods consists of a number of softwoods, such as Balsam Fir, Black Spruce, and Eastern Hemlock.

The most common group of species used in general construction are Southern Pine, Douglas Fir-Larch, and Hem-Fir. Pines are found in southern states from Virginia to Texas, and Douglas Fir is grown along the Pacific coast. Note that terms such as Southern Pine and Douglas Fir, shown in Table 5.2, identify groups of species that may consist of one or more species of similar strength characteristics as shown in Table 5.2.

The mechanical and physical properties of groups of species differ from each other. The species belonging to the Douglas Fir group are strong but rather brittle. California Redwood, a group of species grown along the Pacific coast, is light in weight, soft, straight-grained, and very durable. The heartwood of species belonging to Southern Pine group of species is durable in contact with the ground. In the following sections we describe some important physical and mechanical properties of lumber.

TABLE 5.2 SOFTWOODS LUMBER SPECIES AND SPECIES GROUP

Standard lumber name or species group	Official Forest Service tree or species
Douglas Fir-Larch	Douglas Fir
	Larch
Eastern Softwoods	Balsam Fir
	Black Spruce
	Eastern Hemlock
	Jack Pine
	Red Pine
	Red Spruce
Hem-Fir	California Red Fir
	Grand Fir
	Noble Fir
	Pacific Silver Fir
	Western Hemlock
	White Fir
Northern Pine	Jack Pine
	Norway (Red) Pine
	Pitch Pine
Southern Pine	Loblolly Pine
	Longleaf Pine
	Shortleaf Pine
	Slash Pine
Virginia Pine-Pond Pine	Virginia Pine
	Pond Pine
Western Cedar	Alaska Cedar
	Incense Cedar
	Port Oxford Cedar
	Western Red Cedar

5.1 PHYSICAL PROPERTIES OF WOOD

Two of the most important properties that affect strength and durability characteristics of wood are moisture content and specific gravity. The *moisture content* is the weight of water in wood expressed as a percentage of its oven-dry weight.

$$\text{Moisture content (\%)} = \frac{\text{weight of water}}{\text{oven-dry weight}} \times 100$$

or

$$= \frac{\text{green weight - oven dry weight}}{\text{oven-dry weight}} \times 100$$

The standard method of determining the moisture content has been to dry the wood in an oven to constant weight at 220°F (105°C); however, it is commonly measured using moisture meters. *Specific gravity* is the ratio of the weight of wood to the weight of an equal volume of water. We describe moisture content and specific gravity further in the following sections.

5.1.1 Moisture Content

Wood is a hygroscopic substance, meaning that it has affinity for water in both the liquid and vapor forms. The ability to absorb or lose moisture depends on environmental conditions such as temperature and humidity.

The moisture content in a living tree varies with the species. South American Balsa wood, for example, which is very lightweight and porous, has a moisture content in excess of 400% and has very low specific gravity (about 0.2 or less). A few species, such as Black Ironwood of Florida and White Ash, have very low moisture content with very high specific gravity (about 1.15). Some old-growth Redwood and Western Cedar have high moisture content (>200%), whereas Western Larch and Eastern Hemlock have low moisture content (about 100%). Within any species, there is considerable variation in the moisture content, depending on the age and size of the tree and its location. Typically, trees contain water about two times the weight of its solid material.

The moisture content of a log depends on the part of the log: sapwood versus heartwood. The sapwood of softwood species, in general, has much higher moisture content than the heartwood. For example, sapwood of Western Red cedar has a moisture in excess of 250%, whereas the moisture content in its heartwood is around 60%. The difference in moisture content between sapwood and heartwood is small for hardwoods. For example, sapwood of White Oak has an average moisture content of 78% compared to 64% for its heartwood. Heartwood of common softwoods and hardwoods has moisture content in the range 35 to 100%.

Water exists in wood in two ways: in the cell cavities as *free* water-similar to water in a measuring cylinder-and in the cell walls as *bound water* or *adsorbed water*. (Note that *adsorption* refers to the attraction of water molecules to hydrogen-bonding sites in the cell material.) As long as there remains some water in the cavity, the cell walls remain saturated. The amount of water in cell cavities varies with the amount of drying. This water is the first to be lost when wood is dried. Further drying will remove water from the cell walls. A completely dry wood will absorb free water (in the cell cavities) when exposed to liquid water.

When a log is processed into lumber or particles, the wood begins to lose some of its moisture to the surrounding atmosphere immediately. Lumber has moisture generally in excess of 50% at the time of its manufacture. It can take in or give off moisture depending on the relative humidity of its surroundings. As wood dries, water is driven off the cell cavities. A point is reached when the cavities contain only air and the cell walls are saturated with water, which is called the *fiber saturation point.* The moisture content at the fiber saturation point can vary from 25 to 30% depending on the species.

During the drying period (prior to reaching the fiber saturation point) the volume of wood remains constant as well as most of its mechanical properties, although the density of wood decreases. Below the fiber saturation point, additional drying begins with the removal of water from the cell walls. This stage of drying is followed by a reduction in the cross-sectional dimensions. Almost all properties of wood-physical properties, mechanical properties, resistance to deterioration, and dimensional stability-are affected by the amount of water present in the cell walls. Consequently, the removal of water from the cell walls affects nearly all properties of wood.

When wood is dried below the fiber saturation point, generally during service, lumber assumes a condition of equilibrium, with the final moisture content dependent on the relative humidity, the ambient temperature, and the drying conditions to which it has been subjected. The moisture content at this condition is called *equilibrium moisture content* (EMC). The EMC is also defined as the moisture content at which wood neither gains nor loses moisture to the surrounding air. Its value ranges between 5 and 17% at 70°F and relative humidities between 2 and 80%. Since the relative humidity of the atmosphere does not remain constant, the moisture content of lumber during service fluctuates. Because moisture moves slowly through wood, daily changes in the EMC as the relative humidity changes are barely noticeable.

5.1.2 Density and Specific Gravity

The weight of lumber depends on the species, growth of tree, moisture content, and the part of the log. Green wood (or freshly cut lumber) is heavier than dry wood; green sapwood is heavier than green heartwood, whereas dry heartwood is heavier than dry sapwood. The *density* (or unit weight) of wood is defined as the mass or weight per unit volume. It is directly related to porosity or proportion of the voids.

Both density and volume of wood vary with the moisture content, and thus the two most important physical properties of wood, density and specific gravity, can be measured in different ways. In many parts of the world, wood density is calculated using the total weight of wood, which includes the weight of wood substance and the weight of water. However, in the United States the wood density is found using the oven-dry weight (without water) and the volume at the time of the test (dry weight and green volume).

$$\text{Wood density} = \frac{\text{oven-dry weight}}{\text{volume of green wood}}$$

It was explained earlier that the volume of wood does not remain constant but changes with the moisture content. Accordingly, the density varies with the moisture content, although the oven-dry weight-the numerator in the relationship above-remains unchanged.

Specific gravity is the ratio between the density of wood and the density of water. For example, wood with a specific gravity of 0.5 has a density of 31.2 pcf. The specific gravity is calculated as the ratio between the weight of a given volume of oven-dry wood and the weight of an equal volume of water.

$$\text{Specific gravity} = \frac{W_s}{w_w(V)}$$

where W_s is the oven-dry weight, w_w the density of water, and V the volume of (green)wood.

Wood is composed of solid matter (or wood substance), water, and air. The volume V in the equation above is made up of solid volume, V_s, water volume, V_w• and air volume, V_a. When wood is dried in an oven, water is driven out, and the weight of wood is due to the weight of wood substance, and the volume is equal to V_s plus V_a. Thus irrespective of the moisture content used, the numerator in the equation above remains the same in a sample of wood. But volume Vin the denominator varies with the moisture content, and thus the definition of specific gravity must be qualified by its MC.

The specific gravity is frequently determined in three conditions:

- Green (moisture content in excess of 19%)
- Air-dry (moisture content about 12%)
- Oven-dry

The specific gravity of all wood substance (oven-dry weight, and solid volume V_s only) is approximately l.55. But the specific gravity of a piece of wood or lumber varies from 0.07 to 1.30. Very heavy woods such as Live Oak and Black Ironwood have specific gravity nearly equal to or higher than 1.0 (which means that they are heavier than water), but the specific gravity of very light woods such as Black Cottonwood, Cedar, and Balsam Fir is less than 0.35. Table 5.3 lists some common species of wood and their specific gravity values.

As described earlier, the moisture in the wood has a very large effect on the specific gravity as well as the density. Since the volume of wood decreases with the loss of moisture content below fiber saturation point (due to shrinkage), specific gravity in the green condition is smaller than that measured in air-dry or oven-dry conditions. Specific gravity in the oven-dry condition is the highest. The following equation is recommended in the National Specifications for Wood Construction to calculate the density of wood at any moisture content:

$$\text{density or weight (lb/ft}^3) = \frac{62.4G_0}{1 + 0.009(G_0)MC} \; \frac{[100 + MC]}{100}$$

where G_0 is the specific gravity in oven-dry condition from Table 5.3 and MC is the moisture content in percent.

As indicated earlier, specific gravity is one of the two most important physical properties of wood, and nearly all mechanical properties are related to the specific gravity or the density of wood, which is related to the rate of growth, percent of summerwood, moisture content, and other factors. Strength and stiffness of wood increase, with the

TABLE 5.3 AVERAGE SPECIFIC GRAVITY VALUES OF COMMON SPECIES

Category	Species/species group	Specific gravity	
		Green	Oven dry
Hardwood	Ash, White	0.55	0.62
Hardwood	Aspen	0.36	0.40
Hardwood	Birch, Sweet and Yellow	0.60	0.66
Hardwood	Cottonwood, Black	0.30	0.33
Hardwood	Maple, Black and Sugar	0.55	0.66
Hardwood	Oak, Red	0.53	0.67
Hardwood	Oak, Live	0.80	0.90
Softwood	Cedar, Northern White	0.29	0.31
Softwood	Douglas Fir	0.45	0.51
Softwood	Hem Fir	0.35	0.42
Softwood	Balsam Fir	0.33	0.38
Softwood	Hemlock, Eastern	0.38	0.45
Softwood	Hemlock, Western	0.42	0.48
Softwood	Pine. Longleaf	0.54	0.59
Softwood	Pine, Ponderosa	0.38	0.49
Softwood	Southern Pine	0.50	0.55
Softwood	Redwood	0.35	0.42
Softwood	Spruce, Engelmann	0.33	0.36
Softwood	Spruce, Sitka	0.40	0.43

specific gravity. The effects of changes in the density of wood on various strength characteristics are discussed later.

5.1.3 Examples

EXAMPLES.I

A sample of wood has a moisture content of 24%. Its dimensions are 1.45 x 3.45 x 6 in. The weights of the sample in green and oven-dry conditions are 0.61 lb and 0.55 lb, respectively. Find the specific gravity.

Solution

$$\text{Specific gravity (green)} = \frac{\text{oven-dry weight}}{62.4(\text{green volume})}$$

$$\begin{aligned}\text{Green volume} &= 1.45(3.45)6 \\ &= 30.01\ \text{in}^3 \\ &= 0.0174\ \text{ft}^3\end{aligned}$$

$$\text{Specific gravity (green)} = \frac{0.55}{62.4(0.0174)}$$

$$= 0.51$$

EXAMPLES.2

Find the density of Red Oak at a moisture content of 30%.

Solution From Table 5.3,

Specific gravity in oven-dry condition = 0.67

Moisture content = 30%

$$\text{Density} = \frac{62.4(0.67)}{1 + 0.009(0.67)30}\left[\frac{100 + 30}{100}\right]$$

$$\approx 46 \text{ pcf}$$

5.1.4 Defects

In addition to the two most important properties of wood discussed above, strength and durability of wood are also affected by the presence of defects (imperfections). The *defects* are natural irregularities in the structure of wood. The common defects are cracks, knots, and slope of grain, and occur principally during the growing period and the drying process. They lower the strength and the durability of lumber and should be taken into consideration in design as well as construction. Some of these defects are shown in Fig. 5.2 and explained below.

Cracks occur in various parts of the tree and are given names such as checks, shakes, and splits. Most of these are the result of shrinkage that follows the drying of wood. A *check* is a lengthwise separation of wood occurring across or through the annual rings, usually as a result of seasoning. They may occur anywhere on a piece of lumber.

A *shake* is a lengthwise separation of wood occurring between and parallel to annual rings. A *split* is a complete separation of wood fibers, usually at the ends, throughout the thickness of lumber and parallel to the fiber direction. Both checks and shakes adversely affect the durability of timber because they readily admit moisture, which leads to decay.

A *knot* is a cross section or longitudinal section of branches that were cut with the lumber. Knots displace the clear wood and force the grains to deviate, thus affecting the mechanical properties of wood. They also allow stress concentration to occur. Moreover, knots are harder, denser, and possess different shrinkage characteristics than those of wood tissue.

The term *wood grain* refers to the arrangement of cells or fibers of the wood. Rapidly growing trees having wide annual rings produce coarse-grained wood, whereas those of slower growth produce wood with narrower rings or fine-grained wood. When wood elements do not run parallel to the axis of the piece, it is said to be *cross grained.*

The term *slope of grain* refers to the angle between the direction of fibers and the edge of the piece. For example, a slope of grain of 1 in 20 means that the grain deviates 1 in. from the edge in 20 in. of length along which deviation occurs (Fig. 5.3). The slope of grain is measured and limited at a zone along the length of the piece of lumber that shows the greatest slope.

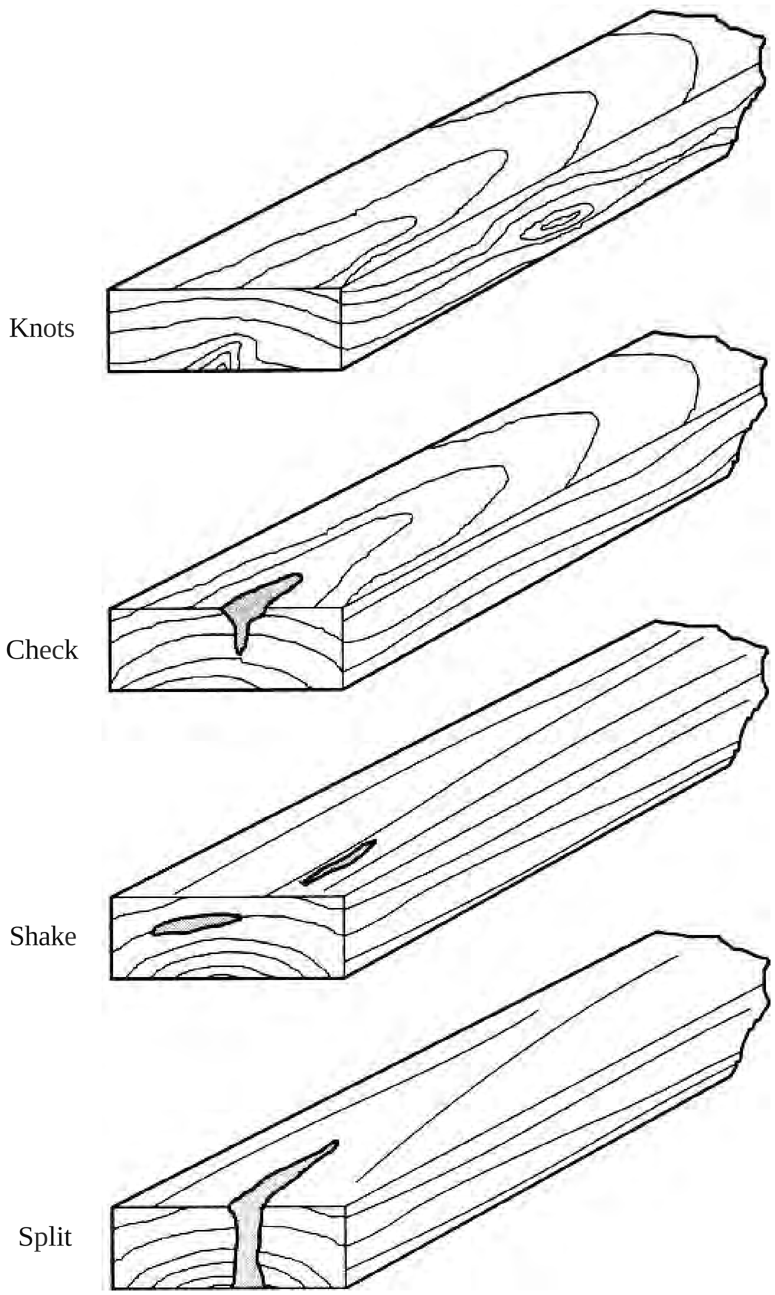


Figure 5.2 Lumber defects.

5.2 SHRINKAGE AND SEASONING

It was mentioned earlier that wood is hygroscopic, meaning that it can absorb or give out moisture. When a log is split into various sizes of lumber the moisture content is normally in excess of 30%, and such lumber is called *green lumber*. The moisture is retained in the cell cavities and the cell walls (bound water). The effects of changes in moisture content on cross-sectional dimensions, and the drying process are discussed in the following sections.

5.2.1 Shrinkage

When the water in the cell cavities evaporates, no reduction in the cross-sectional dimensions (of lumber) is seen. But when the wood dries further, the water is driven out of the cell walls, leading to changes in the cross-sectional dimensions, called *shrinkage* of

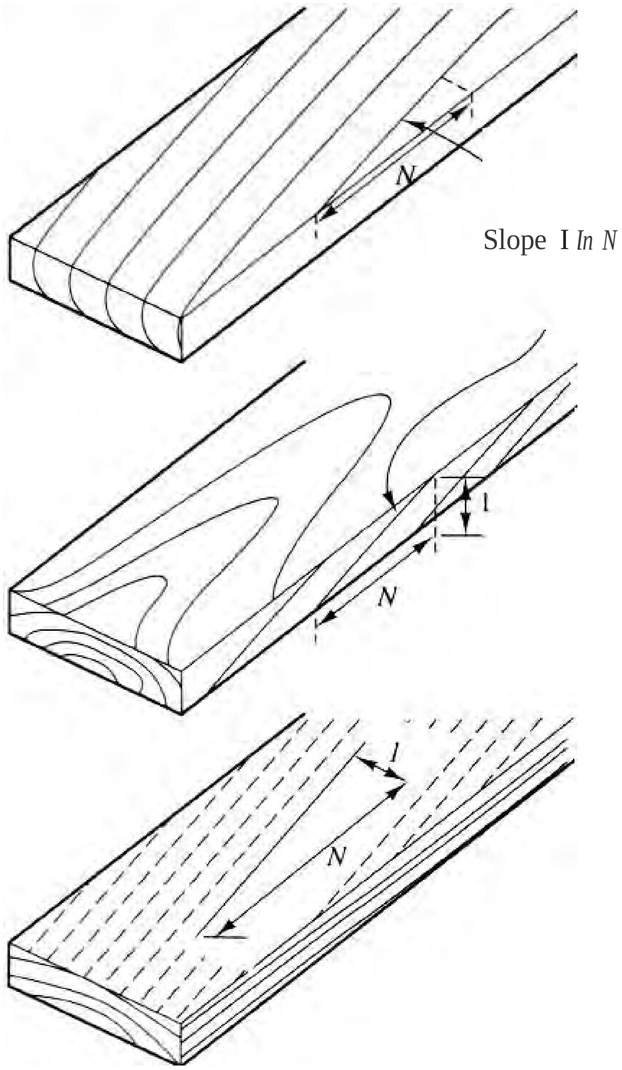


Figure 5.3 Grain pattern and slope of grain.

wood. This shrinkage or reduction in the dimensions varies with the species, thickness of cell walls, arrangement of cells, and grain pattern. Thick-walled cells shrink more than those with this walls, and this inequality in shrinkage (in a particular wood piece) produces stresses in the lumber.

Water evaporates more rapidly from the ends of a wood element than from its side, which action produces bending in the piece. When the stresses (resulting from bending) exceed the tensile strength of wood, longitudinal cracks (normal to annual rings) or checks are produced.

As pointed out earlier, drying of lumber below the fiber saturation point is accompanied by shrinkage. Similarly, a dry piece of lumber will absorb water accompanied by increase in volume, until all the cell walls are saturated, which is the fiber saturation point. The fiber saturation point varies with the species, but generally lies between 25 and 30%. Repeated wetting and drying, and the resulting expansion and contraction weakens the wood, and more important, produces conditions that promote decay.

In general, sapwood of any species will shrink more than will heartwood of the same species. Hardwoods shrink more than softwoods. For example, Oak shrinks considerably and is likely to check during the drying process.

Shrinkage of a log of a tree can be characterized as shrinkage occurring in three mutually perpendicular directions:

- Along its axis
- Along a radial direction (across annual rings)
- Along tangent to the radius (along annual rings)

These three shrinkage directions are identified on a piece of lumber in Fig. 5.4. The *tangential shrinkage* is the highest and is about twice as much as the *radial shrinkage*. The *longitudinal shrinkage* is negligible. The volumetric shrinkage, which is the sum of the shrinkages in all three directions, is about 1.6 times the tangential shrinkage.

It should be noted that shrinkage of each piece of wood is unique since the grain pattern varies from piece to piece. Although it is nearly impossible to predict exactly the nature of shrinkage of any piece of wood, it is fairly reasonable to assume that shrinkage continues in nearly a linear pattern until the lumber is completely dry (Fig. 5.5). This means that the rate of shrinkage is constant.

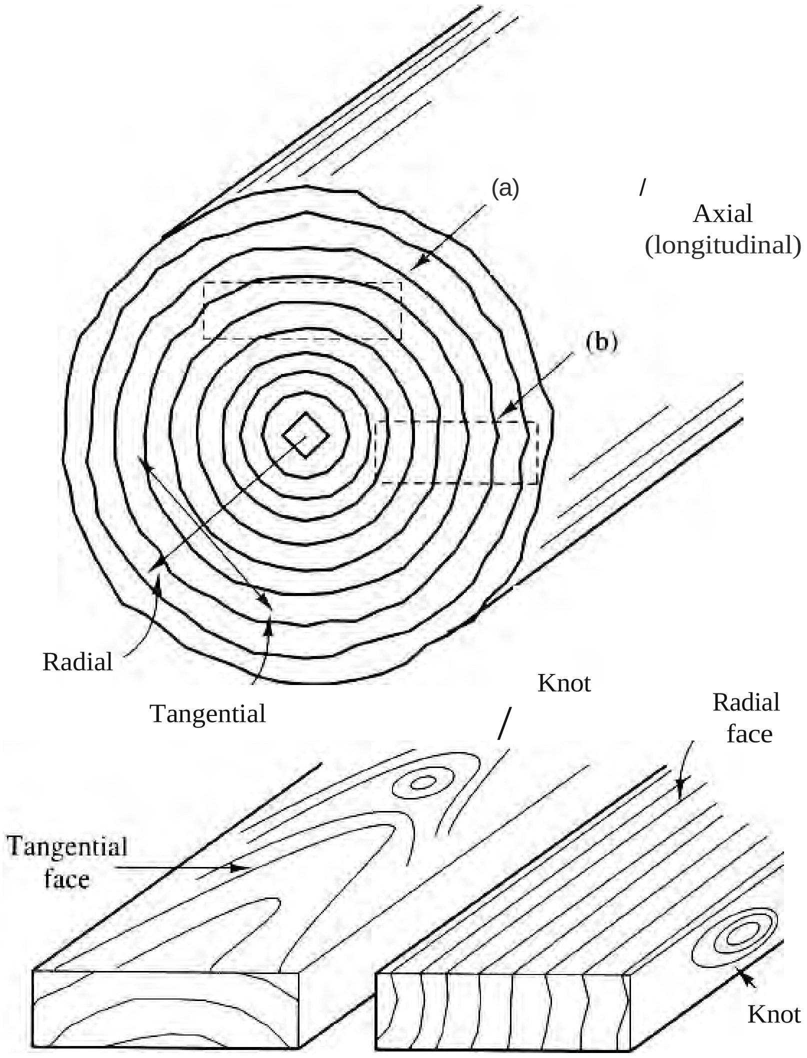


Figure 5.4 Manner of cutting a log: (a) flat-sawn; (b) edge-sawn (quarter-sawn).

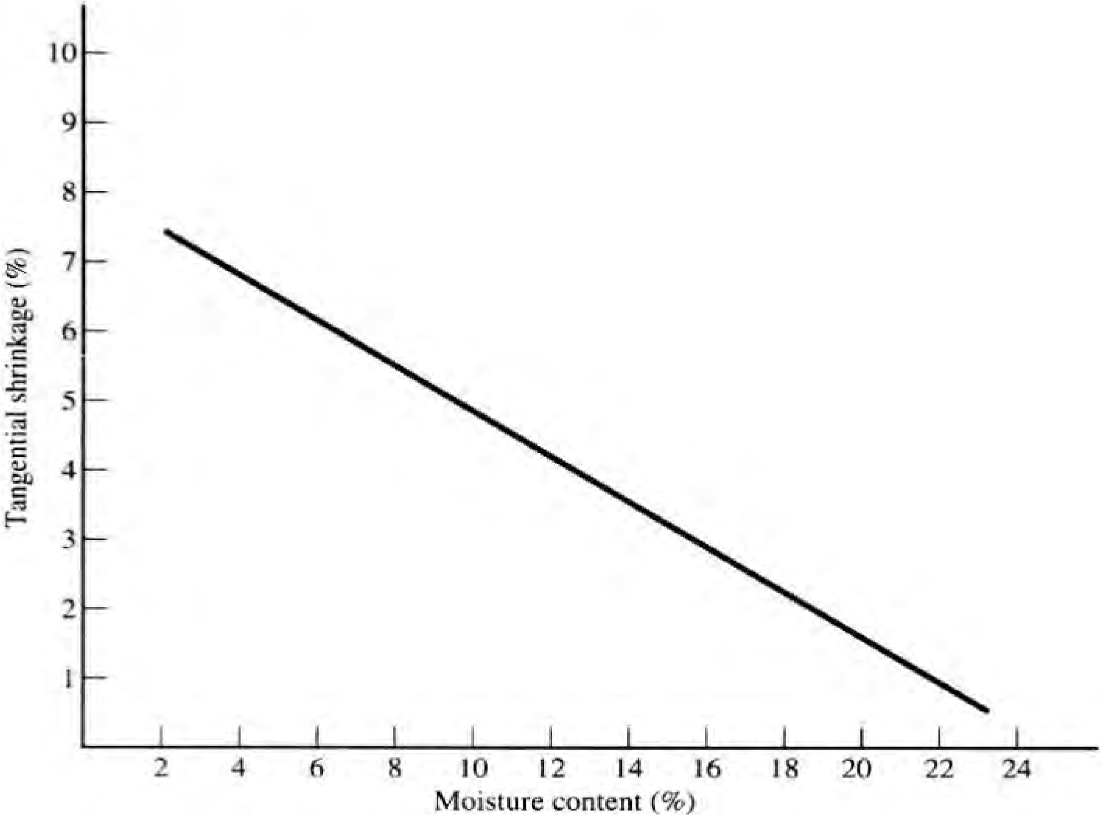


Figure 5.5 Average tangential shrinkage for Douglas Fir.

In general, the volume of wood decreases, on an average, by about 12% when it is dried from fiber saturation point to oven-dry condition. This means that an average value of tangential shrinkage can be assumed as 1% for every 4% decrease in moisture content. For example, the depth of a piece of lumber of width = 2 in. (5 cm) and depth= 14 in. (35 cm) will decrease, on an average, by about 0.7 in. (1.75 cm) when the moisture content decreases from 30% to I 0%. To accommodate this reduction in depth, a floor that is supported on this joist will have to settle by the same amount, and as a result, a number of shrinkage-related problems arise in the finished structure. Shrinkage movement and differential shrinkage between various parts of a building when not taken into consideration, the related problems can affect plumbing fixtures, electrical systems, mechanical systems, and finished surfaces. Cracks in the walls, broken plumbing lines, and cracks in the ceiling can be attributed to the shrinkage in wood.

5..2.2 Seasoning

The process of controlled drying of lumber to increase its structural properties is known as *seasoning.* In addition to an increase in strength characteristics, drying has other advantages, such as lowering of shrinkage in service, improvement in decay resistance, reduction in weight, and better workability. Seasoning is also required to prepare lumber for preservative treatment.

Two methods of drying are practiced:

- Air drying
- Kiln drying

In *air drying,* which is cheaper than kiln drying, lumber is stacked in open-sided sheds so as to promote drying without artificial assistance. Species that dry out slowly are usually stacked in winter so that the lumber will not be affected by the summer heat until its moisture content is relatively low. *Kiln drying* employs a heated, ventilated, and humidified oven; the humidity is essential to control the rate of evaporation of moisture from within the lumber piece.

No matter which method is used to dry or season the lumber, there are only three factors that affect the drying process: temperature, relative humidity, and air circulation. Presently in the United States, seasoning is generally carried out for smaller-sized lumber, and the cost of seasoned lumber is relatively high. Bigger sizes of lumber are marketed as unseasoned or partially seasoned. Softwoods generally take a shorter time to dry than do hardwoods. The sapwood part of the log, which contains most of the moisture, dries out more rapidly than the heartwood part.

5.3 TREATMENT AND DURABILITY

Wood is a very durable construction material and lasts for centuries if it is well seasoned and kept in a dry place, immersed in water, or buried in the ground. However, when subjected to moisture and/or moderate heat, unprotected wood decays. The rapidity with which lumber decays depends on a number of factors, such as species, seasoning, and the environment. In exposed structures such as bridge posts, fence posts, and piles, decay always starts at the sills and the member bottom, where water and snow collect.

Although all species of wood possess some natural resistance to decay, some species are much more durable than the others. *Durability* refers to long-term performance of the material. Most Oaks, Cedars, and Redwood are highly durable, whereas Aspen and Fir are nondurable. The heartwood of all species has very good resistance, while the sapwood is susceptible to decay if not used properly in construction.

For most structural applications, ordinary sawn lumber can be used in the natural form, although coatings such as stains and paints may prolong their service life in an exposed environment. Seasoning of lumber followed by the use of an effective waterproofing technique will render most wood resistant to attack by wood-destroying elements. Paints, stains, and waterproofing chemicals are used to make lumber waterproof. Stains and waterproofing chemicals penetrate farther into the wood than do paints, but none of these materials can be effective when wood is in contact with the ground.

Lumber that is in contact with the ground or is susceptible to decay should be protected through chemical treatment. Wood needs to be *chemically treated* mainly for two reasons:

- To prevent destruction from fungi and insects
- To inhibit combustion

The treatment is carried out by injecting chemicals, under pressure, into the wood fibers, and is called *pressure treatment* or *preservative treatment.* It is generally carried out by incising the surface of lumber by toothed rolls to a depth of½ to ¾ in. (12.5 to 19 mm) and applying pressure until impregnation is complete.

Treatment to prevent destruction from fungi and insects is carried out with one of the three classes of chemicals:

- Pentachlorophenol (Penta)
- Creosote
- Inorganic arsenicals (waterborne preservatives)

These chemicals penetrate deep inside the wood and remain for a long time. Incising is commonly done to provide deeper, more uniform penetration, although some species, such as Ponderosa Pine, can be treated without incising. Proper seasoning is required prior to the treatment.

Penta is a chemical that can be carried in either oil or light hydrocarbon solvent; generally 5% of the solution is made up of Penta. Wood treated with Penta is used for poles, posts, glulam beams, bridges, and marine decking. *Creosote* solutions are derived from coal tar and carried in oil base. Creosote-treated wood is used for piles, poles, and railroad ties. *Waterborne preservatives* can be used for both interior and exterior applications. They leave the treated surface relatively clean, odor-free, and paintable. The most common waterborne preservatives are chromated copper arsenate (CCA), chromated zinc chloride (CZC), and fluor chrome arsenate phenol (FCAP).

Wood treated with Penta or creosote should not be used where it will be in prolonged contact with skin as for furniture and decking. In fact, penta- or creosote-treated wood should not be used in the interior of residential, commercial, or farm buildings. Wood members treated with either of the two chemicals are most suitable when they are in contact with ground. Wood treated with waterborne preservatives may be used inside residential buildings and for patios or decks but should not be used for storage of food items and countertops. Treated wood should not be burned in fireplaces or stoves because of the production of toxic chemicals as part of the smoke or ashes. It is being utilized as a fuel in some industrial boilers and in the generation of electricity. Disposal in landfill is permitted.

The ease with which preservatives can be injected into wood depends on a number of factors, such as density of wood, structure of wood, chemical composition of cell walls, cross-sectional dimensions of lumber, and moisture content. In most species the sapwood is more easily impregnated and absorbs more preservatives than heartwood. The preservative-absorption capacity of the springwood may be different from that of the summerwood. Seasoning facilitates the penetration of preservatives. Smaller-sized lumber can be impregnated more easily than can larger lumber. Pines can be injected more readily than Douglas Fir.

When untreated lumber is not protected properly, it may decay. *Decay* is caused from attack by fungi or insects. *Fungi* are low forms of plant growth, producing thin branching tubes that spread through the wood and use cell walls and lignin as food. With the fungal attack, wood becomes brittle and weak. The attack is further characterized by a lack of resonance when struck with a hammer, the capacity of wood to absorb a large quantity of water, and the unnatural odor and color.

Conditions necessary for fungal growth are:

- Proper temperature
- Moisture content over 19%
- Oxygen
- Food (wood fiber)

Elimination of any one or more of these will effectively control the growth of the organisms. But note that not all fungi thrive equally well under the same surroundings or conditions. For example, a type of fungus known as house fungus can live in seasoned lumber in somewhat dry conditions, a type of decay called *dry rot*.

Dry rot is the most serious of all fungi since once established it can spread rapidly, and the spread may be extensive before visible signs appear. The term *wet rot* is referred to fungal deterioration that occurs in excessively wet lumber. To minimize the dry rot or wet rot condition it is important to eliminate all sources of moisture in the structure, followed by drying out the lumber as well as the building generally with the aid of dehumidifiers.

Another principal cause of wood deterioration is the attack of insects or marine borers. Some insects, such as horntail wasps, round-headed borers, and flat-headed borers, Jive in weakened or drying trees and during the larval stage use wood as the food source. Their activity can be eliminated through the application of heat or steam. A second group of wood-boring insects can live and multiply in dry softwood lumber. The best known of these are termites. Termites, carpenter ants, and white ants live in highly organized colonies and feed on cellulose in the wood. Commonly used wood preservatives such as penta, creosote, or the waterborne salts are toxic to these insects and can be used as eradicants. Termite attack can be prevented by following some precautionary measures during the construction stage, such as building concrete foundations, treating wood that is in contact with the ground, and providing sheet metal shields for all sills and foundation lumber.

In addition to fungi and insects, fire destroys the wood, decomposing it into carbon dioxide, water vapor, and ash. *Fire resistance* of wood depends on the species, temperature, and moisture content. Dry or well-seasoned lumber will ignite with difficulty at temperature below 400°F (204°C) but very quickly when the temperature exceeds 600°F (316°C). Green lumber is about twice as resistant to fire as is dry lumber.

5.4 LUMBER SIZES

There are a large number of commercially important softwood species that are used in construction, and lumber from several of the species share the performance characteristics. These species are also similar enough in appearance that they are grouped together into "marketing categories." For example, Douglas Fir and Larch often are alike and have similar properties, and as a result, are marketed under one category: Douglas Fir-Larch.

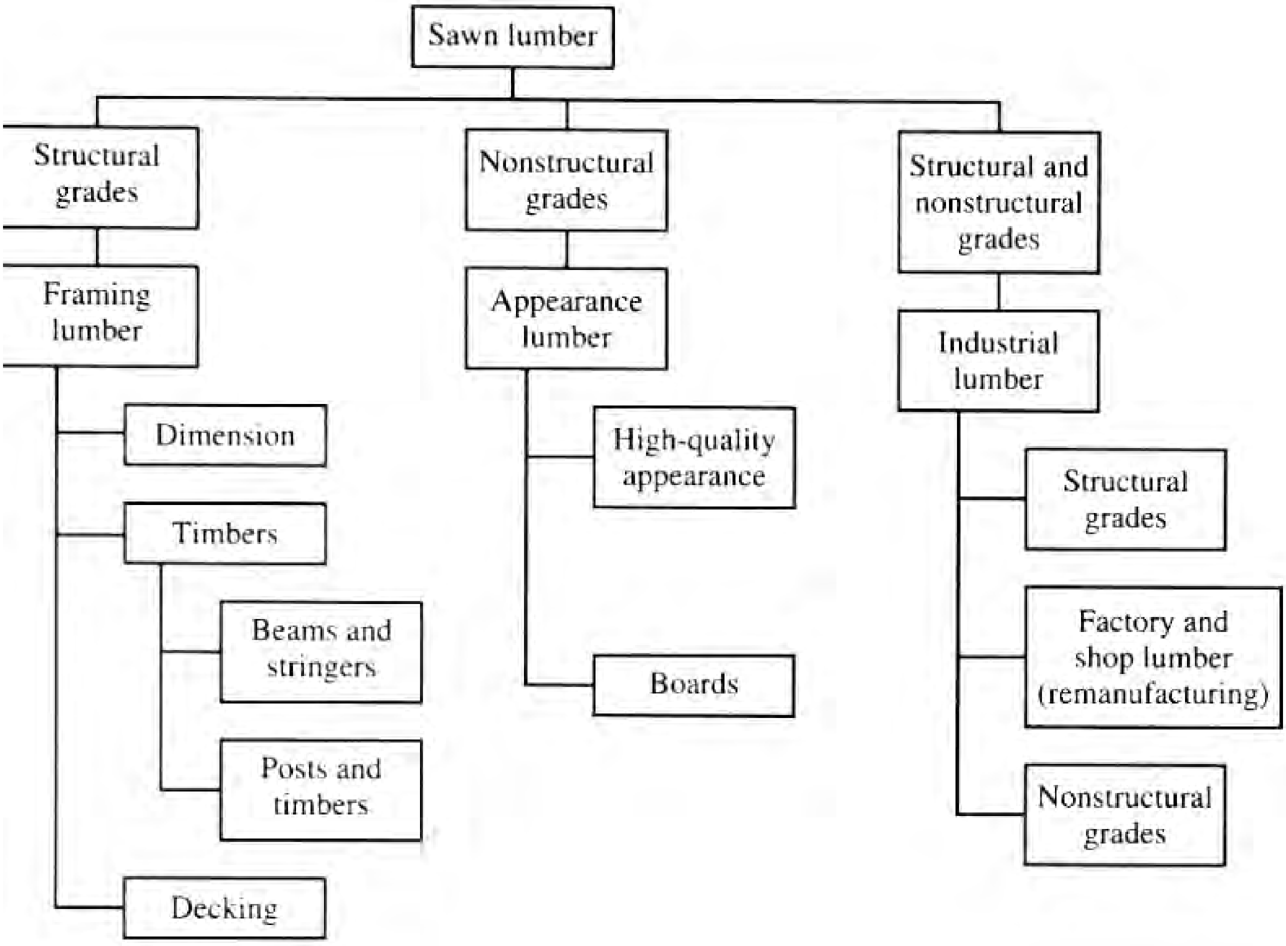


Figure 5.6 Sawn lumber categories.

But the shipments (containing the Douglas Fir-Larch mark) need not contain both species. The most common combination species and the species that are included in this combination (species group) were noted earlier and listed in Table 5.2.

Lumber can be broadly classified as:

- Framing lumber
- Appearance lumber
- Industrial lumber

Framing lumber (Fig. 5.6) includes the grades intended for structural applications in both conventional and pre-engineered framing systems. For example, lumber for joists, posts, and trusses is the framing lumber. This type of lumber is graded based on its strength properties, or is structural graded. *Appearance lumber* includes a variety of nonstructural grades intended for applications where strength properties are not the primary consideration. Many of the products used in applications for paneling and siding belong to appearance lumber. Its grade reflects a judgment of appearance and suitability to end use. *Industrial lumber* represents a broad category of structural and nonstructural grades intended for a variety of specific applications, such as mining, scaffolding, and foundation. Unless stated otherwise, any reference to lumber in the following sections should be assumed to refer to framing lumber. It should be noted that only lumber that is structural graded should be used in engineered applications.

Softwood lumber is a manufactured wood, in that it is derived from a softwood log in a mill, and in a rough stage is sawed, edged, and trimmed at least to the extent that it shows saw marks on four longitudinal surfaces. *Rough lumber* has surface imperfections caused by the primary sawing operations, whereas *dressed lumber* is planned or sanded on combinations of sides and edges. The term S4S is used to identify lumber that is surfaced on all four sides. Such a piece of lumber is identified by its *nominal size,* which is a commercial size designation of the thickness and *the* width (or depth) of standard sawn lumber. The *dressed size* or *net size* is the size assumed to be obtained by dressing the lumber-using a planing machine on a combination of sides and edges-and is the size used in all structural calculations. This size is smaller than the nominal size by ½2 to ¾ in., (6 mm to 19 mm) depending on the size category and moisture content as shown in Table 5.4. For example, lumber of nominal size 4 x 16 has dressed size (dry condition) 3½ x 15¼ in. The cross-sectional properties, such as area, moment of

TABLE 5.4 NOMINAL AND DRESSED SIZES OF **SAWN** LUMBER

Use category	Thickness (in.)			Width (in.)		
		Minimum dressed			Minimum dressed	
	Nominal	Dry	Green	Nominal	Dry	Green
Boards	1-1½	¾	25/32	2	l½	I'1/,6
		1¼	1%	3	2½	2%
				4	3½	3'½.
				5	4½	4¾
				6	5½	5¾
				7	6½	6¾
				8	7¼	7½
				9	8¼	8½
				10--16	¾ less than nominal	½ less than nominal
Dimension	2-4	½ less than nominal	7/16 less than nominal	2-4	½ less than nominal	½6 less than nominal
				5, 6	½ less than nominal	¾ less than nominal
				8-16	¾ less than nominal	½ less than nominal
Timbers	5 and larger		½ less than nominal	5 and greater		½ less than nominal
Decking [a]	2-4	½ less than nominal		4-6	I less than nominal	
				8-12	I¼ less than nominal	

[a] Dressed width shown is the face width.

inertia, and section modulus are based on the dressed size (dry condition). Unseasoned lumber is manufactured oversized so that when it reaches the dry state its size is approximately the same as the dry-dressed size.

Generally, lumber is manufactured in standard sizes starting with nominal size 2 x 2 (thickness of 2 in. nominal and width of 2 in. nominal) and in increments of 2 in. (thickness as well as width). Thus, common thicknesses are 2, 4, 6, and 8 in., and common widths are 2, 4, 6, 8, 10, 12, 14, and 16 in. In a typical wood construction, if a particular size is not feasible, one has to choose the next-higher size in 2-in. thickness or width increments. For example, if 2 x 10 is found inadequate, a 2 x 12 should be tried.

Board foot is the unit of measurement for most lumber items. It is defined as a piece I inch thick (nominal) by 1 foot wide (nominal) by 1 foot long (actual), and is calculated as follows:

$$\text{board foot} = \frac{t \times w \times L}{12}$$

where t is the nominal thickness in inches, w the nominal width in inches, and L the length in feet. For example, 12 pieces of nominal 2 x 4 lumber 12 ft long measures

$$= \frac{2 \times 4 \times 12}{12} \times 12 = 96 \text{ board feet}$$

Untreated lumber may begin to dry in outdoor storage if stored in warm weather for an extended time, causing splits, checks, and warp. To prevent deterioration, lumber in storage yards should be stacked on stringers off the ground. This procedure allows for air circulation and aids in handling. In a job site, lumber should be unloaded in a dry place. Untreated lumber should be placed in stringers or short pieces of lumber. To prevent excessive moisture gain, lumber should be covered with a plastic sheet or similar weather-protective materials.

5.5 USE CLASSIFICATION AND LUMBER GRADING

Softwood lumber is classified for market use by species, form of manufacture, and grade. *Grade* designates the quality of lumber or wood product. Generally, the grade of a piece of lumber is based on defects, imperfections, and other features that may lower its strength, durability, and utility value.

Hardwood lumber grading in the United States is carried out based on the Rules for the Measurement and Inspection of Hardwood and Cypress Lumber, drafted by the National Hardwood Lumber Association (Memphis, Tennessee). Some hardwoods, suitable for construction, are graded using the rules for softwood.

Softwood lumber grading is based on general guidelines set in the American Softwood Lumber Standards issued in 1970 (PS20-70). But a number of softwood lumber trade associations, such as West Coast Lumber Inspection Bureau (WCLIB), Western Wood Products Association (WWPA), and Southern Pine Inspection Bureau (SPIB), prepare their own grading rules that apply to their species. Hardwood and softwood grading rules differ in principle. Hardwood is used predominantly for cabinetry, whereas softwood is used by carpenters in construction.

Softwood grade depends on the effect of defects and imperfections on strength and deformation-mechanical properties-of that lumber. It can be considered in the context of two major categories of use:

- Construction
- Remanufacture

The term *construction* (Fig. 5.7) refers to lumber that will reach the consumer as graded and sized after primary processing (sawing and planning), whereas the term *remanufacture* refers to lumber that will undergo a number of manufacturing steps before it reaches the consumer. A construction lumber piece does not undergo further grading once it leaves the sawmill.

The construction grade is divided into three general categories:

- Stress-graded lumber
- Non-stress-graded lumber
- Appearance lumber

Stress-graded lumber (also *called framing lumber* in the earlier section) and non-stress-graded lumber are used in applications where the structural integrity is the primary requirement, and *appearance lumber* is for use in applications where the appearance (and not the structural integrity) is of primary importance. Stress-graded lumber or framing lumber is lumber of any thickness and width that is graded for its mechanical properties. Lumber retailers also carry yard lumber or common lumber, which is a general term for *non-stress-graded lumber*, which has an appearance quality lower than of select grade but is suitable for general construction and utility purposes (e.g., redwood con-common and con-heart). Note that select lumber is a general term for lumber of good

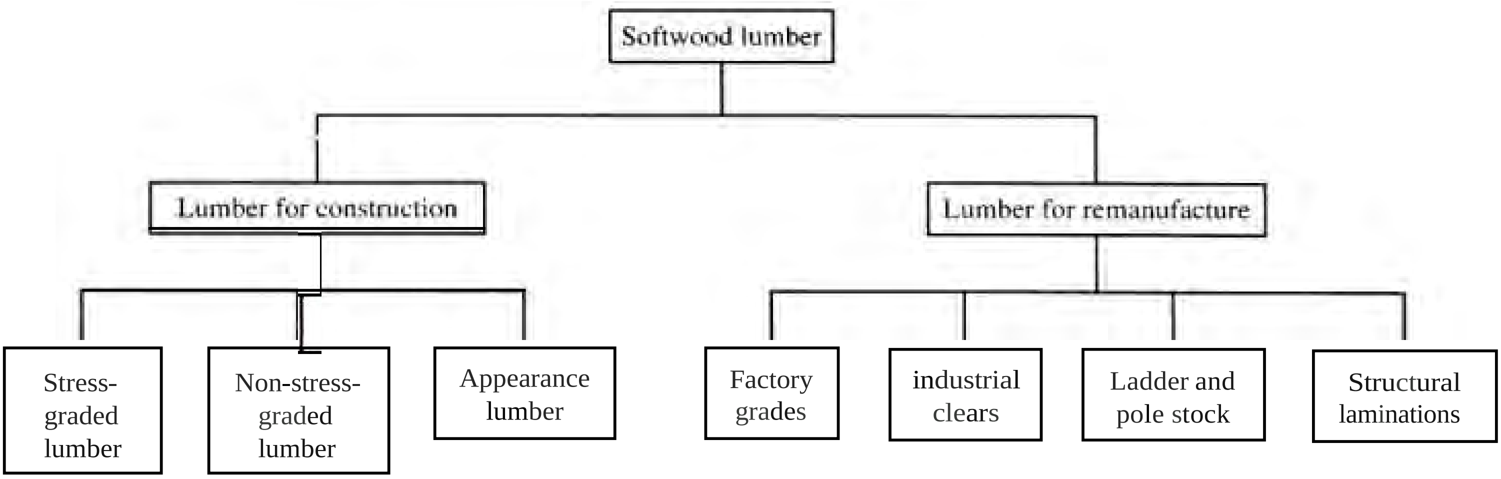


Figure 5.7 Softwood lumber grades.

appearance and finishing qualities. The fo11owing discussions apply to stress-graded lumber only.

When a log is sawed into lumber, the various pieces differ in quality, strength, serviceability, and value. Individual pieces will have different characteristics with respect to freedom from knots, cross grain, shakes, and so on (Fig. 5.2). To standardize the mechanical properties of lumber, a stress-grading scheme has been established which is referred to as *stress grading* or *structural grading.*

Under the stress-grading system of classification of lumber, the grade description of a piece of lumber depends on its intended use and structural defects or imperfections and is independent of the species and the geographical region in which it is produced. However, allowable values of a certain grade of lumber, belonging to an individual species, may be different from those of other species, due to variations in specific gravity and mechanical properties. For example, a nominal 2 x 8 lumber of grade 1 and species group Douglas Fir-Larch has an allowable bending stress dissimilar to that of grade- I, 2 x 8 lumber of species group Southern Pine.

The building codes around the country require that only *grade-marked lumber* be used for all structural applications. This mark or *grade stamp,* which is seen in all structural or framing lumber, provides the grade of that piece of lumber. The grade is estimated based on inspection of physical characteristics that affect the mechanical properties of lumber.

As noted earlier, the *grade* (structural) of a piece of lumber (stress graded) is based on two aspects: anticipated end use--called size or use classification-of the lumber and its defects. This means that grade of a piece of lumber depends on response to two hypothetical questions: (1) what is the type of load the member is expected to carry, and (2) what is the nature and extent of imperfections? Response to the first question is set in the Softwood Lumber Standards as size classification rules.

The *size classification* or *use classification* rules are based on the anticipated end use of a piece of lumber considering only its size (cross-sectional dimensions), even though no restrictions exist on the actual use in any construction. For example, because of its square cross section, a 6 x 6 lumber (meaning a nominal cross section 6 in. in thickness and 6 in. in width) is suitable for use as a post or column and is thus classified (and graded) under the Post and Timber category. But it should be noted that this square piece of lumber may very well be used as a beam or beam-column, the choice being left to the designer.

5.5.1 Dimension, Timbers and Decking

In general, according to size classification rules, framing lumber is divided into three classes:

- Dimension lumber
- Decking
- Timbers

Dimension lumber (Table 5.5 and Fig. 5.8) refers to any piece of rectangular cross section, 2 to 4 in. nominal in its least dimension (thickness), graded primarily for strength in bending edgewise or flatwise but also frequently used where tensile or compressive strength is important. For example, lumber of nominal size 2 x 4, 2 x 8, 4 x 4, and so on, belong to this category. This class of lumber is designed for use as joists, planks, rafters, studs, and so on.

Dimension lumber is subdivided into four use categories:

- Light framing
- Structural light framing

TABLE 5.5 SIZE (USE) CLASSIFICATION OF STRESS-GRADED SAWN LUMBER

Size or use classification	Subcategory	Nominal thickness (in.)	Nominal width (in.)	Example	Uses
Dimension	Structural light framing and light framing	2-4	>:2	2X2, 2X4, 4X4,4X12, 4 X 16	Joists, rafters, studs, truss members
	Studs				
	Structural joists and planks				
Decking		2-4	4-12	2 X4, 2 X 8, 4X8	Floor decking, roof decking, solid wall
Timbers	Beams and stringers	>:5	>(2+ Thickness)	6 X 10, 6 X 12 8 X 12	Beams, headers
	Posts and timbers	>5	> (2+ Thickness)	6 X 6, 6 X 8, 8X8	Columns, posts

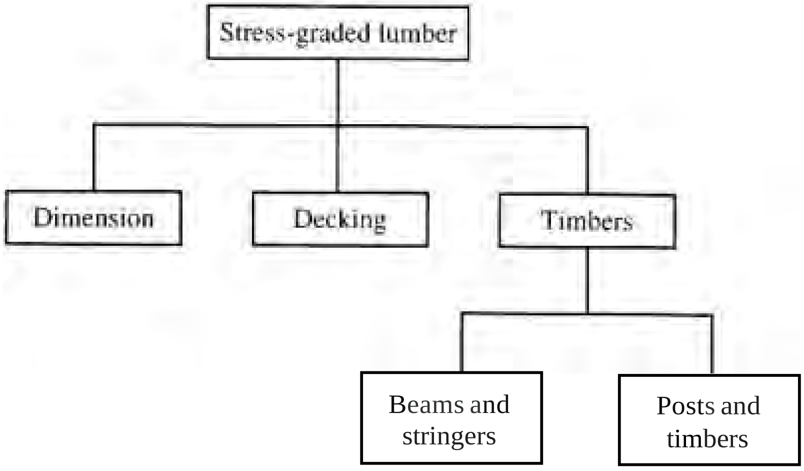


Figure 5.8 Size classification.

- Studs
- Structural joists and planks

Structural light framing and *light framing* are 2 to 4 in. wide, studs are 2 to 6 in. wide, and *structural joists and planks* are 5 in. and wider. *Stud-grade* lumber is used as studs in load-bearing walls, and joists and planks are fit for use as floor joists, rafters, headers, beams, and truss members.

A special Dimension category, called *Decking,* refers to lumber 2 to 4 in. thick and 4 to 12 in. wide, tongue and grooved or grooved for spline on the narrow face, and intended for use in roof, floor, and wall construction. It is graded for application in the flatwise direction with loads applied on the wide face. *Timber* is both a general classify-cation for the larger sizes of framing lumber and the name of a specific grade and size.

There are two basic grade groups within the Timber size classification:

- Beams and Stringers
- Posts and Timbers

The *Beams and Stringers* classification includes pieces of rectangular cross section, 5 in. and thicker, and width more than 2 in. greater than the thickness. It is graded for strength in bending when loaded on the narrow face and is used primarily when materials larger than Dimension lumber is required to carry flexural loads (e.g., 6 x 10, 8 x 12, 8 x 24, etc.). The *Posts and Timbers* classification represents lumber that is approximately square in cross section, 5 x 5 in. nominal dimensions and larger (width not more than 2 in. greater than the thickness), and graded primarily for use as posts and columns. Posts and Timbers are meant for use in construction where materials larger than square Dimension lumber is required. Sizes such as 6 x 6, 8 x 8, and 6 x 8 belong in the Post and Timbers category.

Dimension is the principal stress-graded lumber item available in a lumberyard and is used primarily in light construction for joists, rafters, and studs. It is found in nominal 2-, 4-, 6-, 8-, 10- and 12-in. widths, and 8- to 18-ft lengths in multiples of 2 ft. Longer than 18 ft is not commonly available in many lumberyards. In the non-stress-graded category, the shape and size of the lumber combined with some grading requirements are used to provide a measure of structural integrity. *Boards,* which is lumber less than 2 in. in nominal thickness, is the most important non-stress-graded softwood lumber. This type of lumber is used for siding, cornice, shelving, and paneling.

5.6 TYPE OF GRADING, GRADE STAMP, AND MOISTURE CONTENT CLASSIFICATION

Softwood lumber is manufactured in length multiples of 1 ft, but in practice, multiples of 2 ft (in even numbers such as 6, 8, 10, and 12 ft) are the most common. In the United States the board measure is in common use for lumber. A *board foot,* which is a volume measurement, represents a piece of lumber that is I ft long, I ft wide, and I in. thick (based on nominal dimensions). Thus a nominal 2 x 6 in., lumber that is 24 ft long has a volume of 24 board feet (also refer Section 5.4).

5.6.1 Moisture Content Classification

Softwood lumber is surfaced in green or dry condition depending on the size classification. Dimension and Board lumber may be surfaced green or dry, and both green and dry standard sizes are given in Table 5.4. The sizes of green lumber are such that when the lumber shrinks, it will have a size approximately that of dry lumber. Timbers (Beams and Stringers and Posts and Timbers categories) are usually surfaced while green, and only green sizes are given.

The terms *green* and *dry* lumber express the minimum moisture content in a piece of lumber during the surfacing operation. Softwood lumber has three moisture content classifications:

- Surfaced dry (or S-Dry)
- Surfaced green (or S-Grn)
- 15% maximum moisture content (or MC15)

Softwood lumber that is dried to 19% moisture content or less is the dry lumber and is identified as *S-Dry*, which is shown on the grade stamp. On an average, the actual moisture content in these lumber pieces may be around 15%. Lumber that is kiln dried to a maximum moisture content of 15% is called *MCJ 5* lumber and has that mark on the grade stamp. When the moisture content is in excess of 19% it is called the green lumber and the grade stamp shows the identification mark *S-Grn*.

If the moisture content is critical in any construction, the moisture content grade should be specified. Note that the grade stamp marks, S-Grn, S-Dry, or MC15 (in the grade stamp; Fig. 5.9), do not represent the moisture content existing in any piece of lumber, but express the moisture content during the lumber manufacture.

5.6.2 Grading

As explained in Section 5.6.1, most lumber is graded based on some uniform grading rules. The grading is carried out under the supervision of inspection bureaus or grading agencies, some of which also author grading rules for the species in the geographic regions they represent. But to provide for a uniform grading procedure and rules, many of the rules and the standards follow the American Softwood Lumber Standards, PS20-70.

Stress-grading rules incorporate a sorting or grading criterion, a set of allowable values (mechanical properties for engineering design), and a grade name. The grading or sorting is accomplished *visually* or through *nondestructive measurements* (also called *E-Rated),* such as the bending stiffness. Up to six allowable properties are associated with a stress grade (Fig. 5.10):

- Modulus of elasticity
- Tensile stress parallel to grain
- Compressive stress parallel to grain

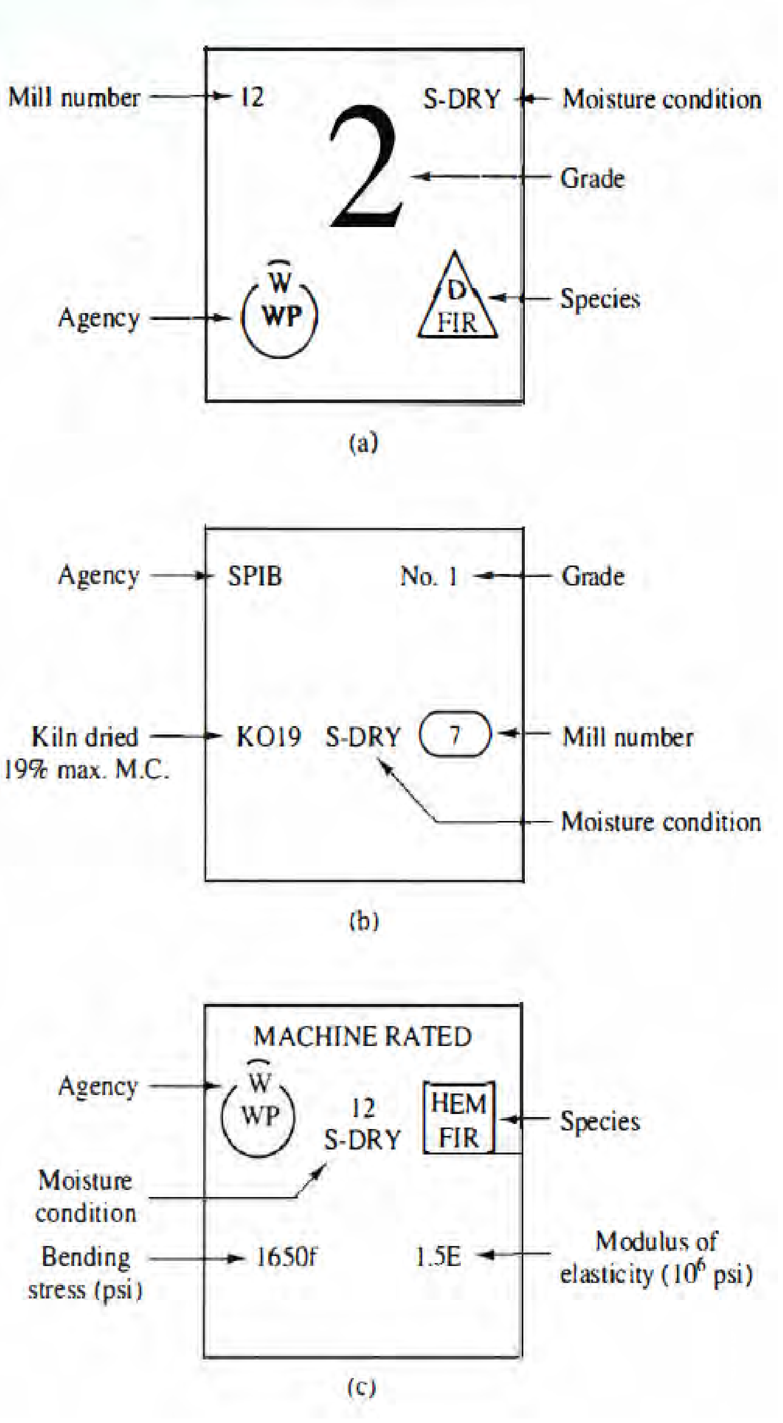


Figure 5.9 Typical grade stamps: (a, b) visual grading; (c) machine grading.

- Compressive stress perpendicular to grain
- Shear stress parallel to grain
- Bending stress

All lumber manufactured for use in structural applications (in which the sizes are determined based on the mechanical properties of the lumber) are stress graded and grade stamped to that effect. This also means that lumber that does not have the grade stamp (stress grade) should not be used in light construction.

Grade stamp. The grade name of a piece of lumber is shown on its grade stamp. The typical stress grades for visually graded lumber are Select Structural, No. 1,

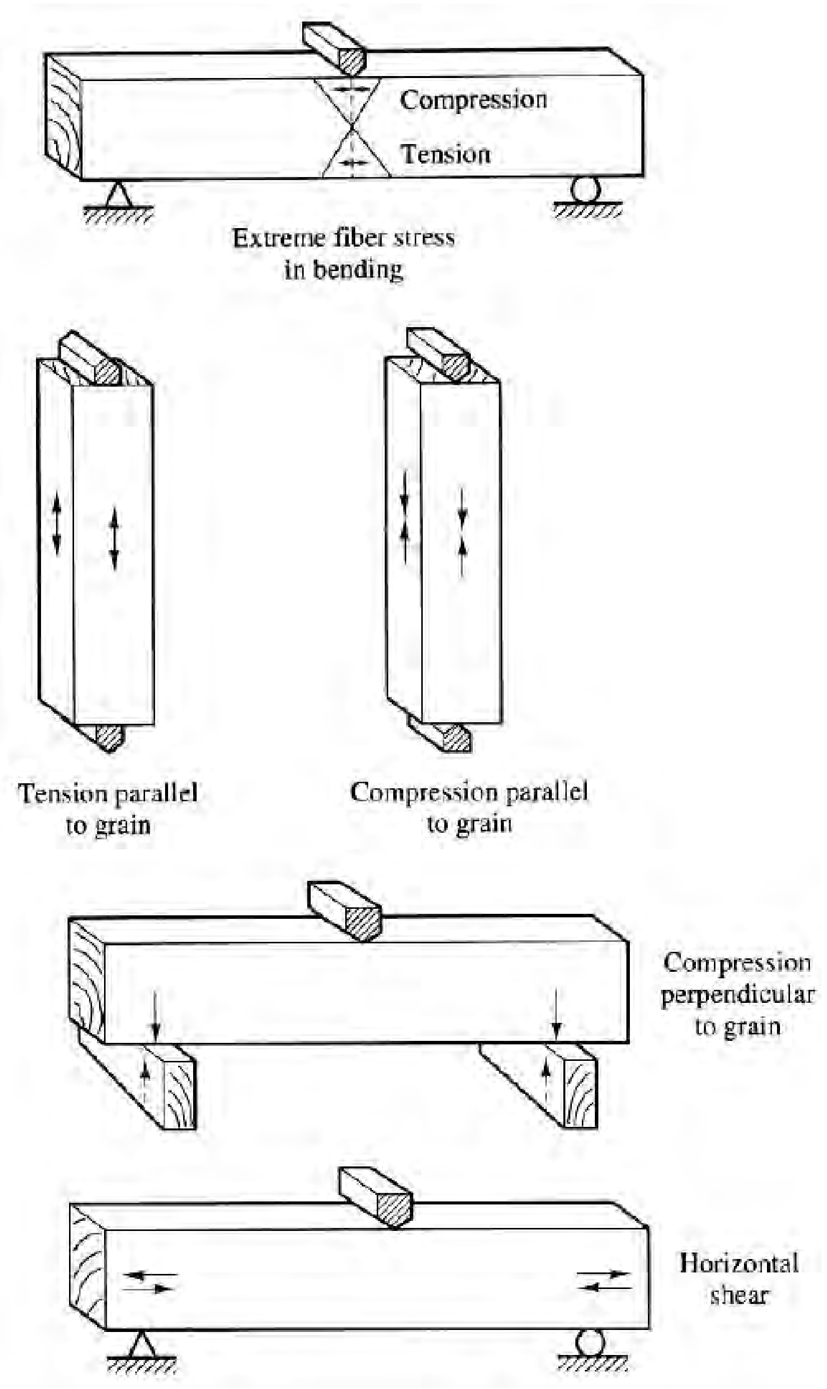

Compression
Tension
Extreme fiber stress in bending
Tension parallel to grain
Compression parallel to grain
Compression perpendicular to grain
Horizontal shear

Figure 5.10 **Types** of stress.

No. 2, and so on. In addition to the grade (or grade name), a grade stamp also provides other information, such as species name and moisture content classification.

Typical grade stamps of visually graded lumber are shown in Fig. 5.9. Grade stamp contains information on species (D-Fir), grade (No. l), moisture content classification (S-Grn), agency **(WWP),** and mill number (12). Visual grading is the oldest stress-grading method and is based on the premise that mechanical properties of lumber differ from those of clear wood specimens of the same species because there are many growth characteristics that can be seen and judged by the eye which affect these properties. Here *clear wood* is defined as lumber that does not contain characteristics such as knots, cross grain, checks, and splits. The growth characteristics used to sort lumber into stress grades are density (number of annual rings per inch and percent of summerwood), decay, slope of grain, knots, and cracks.

In the nondestructive system of grading or E-rating (called MSR lumber), the stress rating equipment measures the stiffness of the material and sorts it into various modulus of elasticity classes. Following the assignment of E values, each piece must also meet certain visual requirements. The modulus of elasticity values are then used to predict the bending strength or modulus of rupture and the tensile strength of the lumber. The higher the E value, the higher are the modulus of rupture and tensile strength. At present only small-sized lumber (2 x 4 nominal) is available as E-rated. When specifying the MSR lumber, the bending stress (allowable) and modulus of elasticity values should be specified.

The grade stamp of E-rated lumber differs from that of the visually graded in the grade name designation. In visually graded lumber, as seen earlier, the grade stamp shows the grade of the piece of lumber, whereas in the E-rated lumber piece, modulus of elasticity (in million psi) and allowable bending stress (in psi) are shown in the grade stamp. Figure 5.9c shows a typical grade stamp of E-rated lumber, where 1.5E represents the modulus of elasticity and 1650f represents the allowable value in bending. Note that other information in the grade stamp is the same as that in the grade stamp of visually graded lumber.

5.7 MECHANICAL PROPERTIES AND ALLOWABLE VALUES

Wood has unique independent properties in the three mutually perpendicular axes: longitudinal, radial, and tangential (Fig. 5.4). The longitudinal axis is parallel to the grain, the tangential axis is perpendicular to the grain but tangent to the annual rings, and the radial axis is normal to the annual rings (and perpendicular to the grain direction).

Modulus of elasticity. The *modulus of elasticity* in the longitudinal direction is the highest and is between 1 and 2 x 10^6 psi (6.9 and 13.8 x 10^3 MPa) (at 12% moisture content), depending on the species. The modulus of elasticity of many hardwoods (such as Birch, Hickory, and Oak) is closer to or higher than the high range, but that of many softwoods (such as Douglas Fir, Hemlock, Redwood, and Loblolly Pine) is closer to the low range. The modulus of elasticity (both parallel and perpendicular to grain) depends on the moisture content, and decreases (from dry condition) 1 to 3% for every 1% increase in the moisture content (Fig. 5.11). For example, the modulus of elasticity (parallel to grain) of Western Hemlock at 12% moisture content is 1.63 x 10^6 psi (11.2 x 10^3 MPa) whereas it is 1.31 x 10^6 psi (9 x 10^3 MPa) in green condition. In a particular species the modulus of elasticity as well as other mechanical properties increase with the amount of summerwood. The modulus of elasticity in the radial direction is about 10% of that in longitudinal direction, and that in the tangential direction is about one-half of that in the radial direction.

Compressive strength. The *compressive strength* of lumber parallel to the grain is much higher than that perpendicular to grain. Columns, posts, and members of a truss are subjected to axial loads parallel to the grain of wood. When a column rests on a

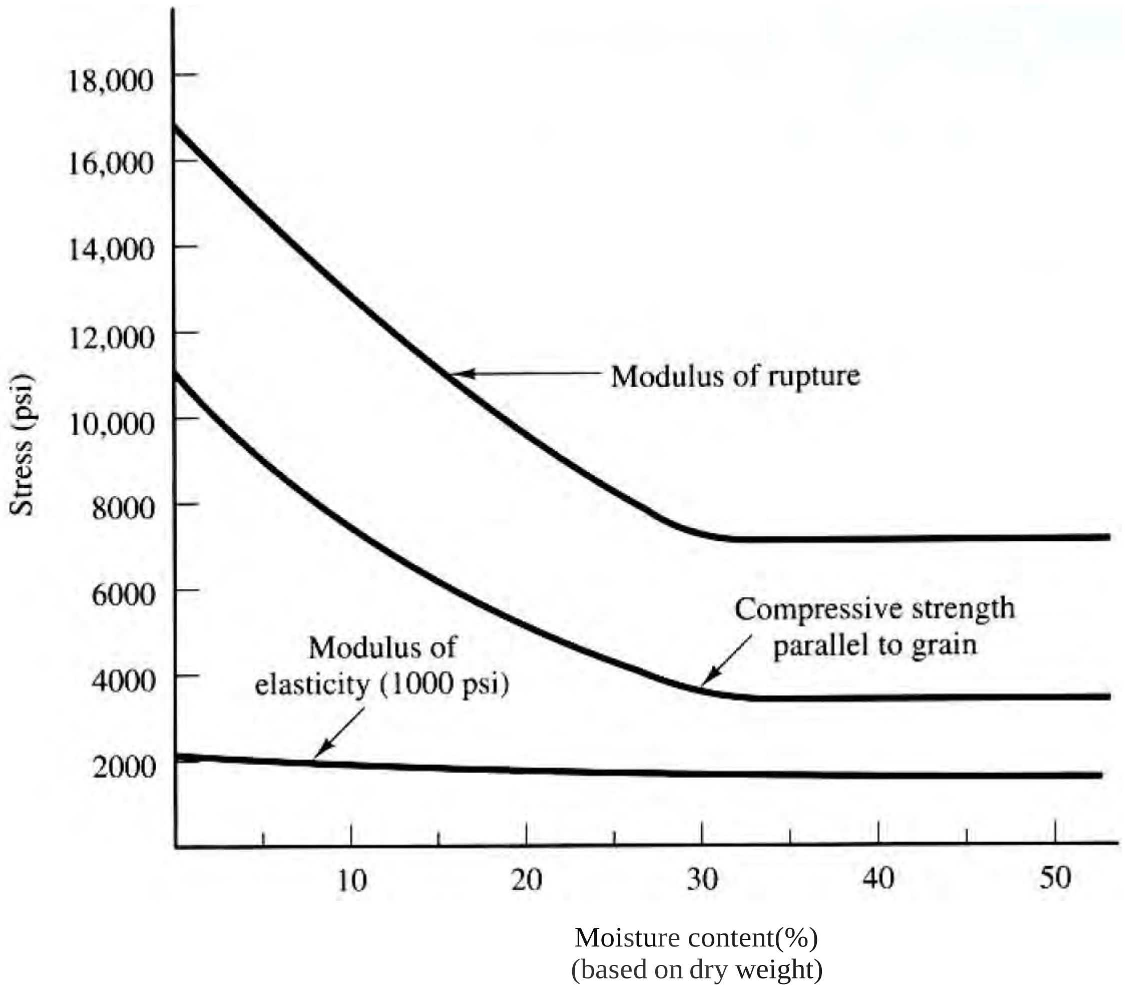


Figure 5.11 Effect of moisture content on strengths of small clear specimens of Western Hemlock.

beam the load from the column creates compressive stress (bearing) on the beam that is perpendicular to the grain of wood.

The compressive strength of most softwood lumber parallel to grain is in the range 2000 to 4000 psi (13.8 to 27.6 MPa) (green condition). The stress at the proportional limit is about 80% of this strength. The compressive strength perpendicular to the grain varies between 12 and 18% of that parallel to grain. The compressive stress at the proportional limit, for loading perpendicular to the grain, is about 12 to 25% of that for loading parallel to grain. In dry condition lumber can possess significantly higher compressive strength (Table 5.6). For example, the compressive strength (parallel to grain) of Douglas Fir in green condition is about 3700 psi (25.5 MPa), while that at 12% moisture content is about 7000 psi (48.2 MPa). Seasoning increases the compressive strength. Typically, the compressive strength (parallel and perpendicular to grain) increases an average 4 to 6% for every 1% decrease in moisture content (Fig. 5.11). Species such as Oak, Maple, Douglas Fir, Southern Yellow Pine, and Western Larch possess very high compressive strengths.

Bending strength. Lumber has very good *bending strength*, and combined with its lightness, remains one of the important flexural materials in light construction. It is used as beams, joists, rafters, headers, and other members that are subjected to bending moment.

TABLE 5.6 AVERAGE MECHANICAL PROPERTIES OF SOME COMMON SOFTWOODS[8]

Species	Modulus of rupture (psi)	Modulus of elasticity (Million psi)	Compression parallel to grain (psi)	Compression perpendicular to grain (psi)	Tension parallel to grain (psi)	Tension perpendicular to grain (psi)	Shear parallel to grain (psi)
Northern White Cedar	6,500	0.8	4,000	310		240	850
We-stem Red Cedar	7,500	I.I	4,500	460	8,600	220	900
Douglas Fir	12,500	1.5-1.8	6,200-7,200	750	20,000	350	1,100-1,500
Hemlock	6,500-12,000	1.2-1.6	5,500-7,200	550-850	17,000	350	1,000-1,500
Western Larch	13,000	1.85	7,500	930	21,000	430	1,300
Ponderosa Pine	9.400	1.30	5,300	580	11,000	420	1,100
Virginia Pine	13,000	1.52	6,700	910	17,500	380	1,300
Redwood	8,000-10,000	1.1-1.3	5,200-6,200	500-700	12,000	250	950-1,100
Sitka Spruce	10.000	1.5	5,600	580	11,000	370	1,100

[3] Based on clear wood tests at 12% moisture content.

You may recall from a course in strength of materials that stress f, resulting from bending moment M, can be calculated from the flexural formula

$$f = \pm \frac{My}{I}$$

where f is measured at distance y from the neutral axis and / is the moment of inertia of the cross section about the bending axis. The maximum stress or stress at the extreme fiber can be found as

$$f = \pm \frac{Mc}{I}$$

where c is the distance from the neutral axis to extreme fiber.

Although the two equations above are commonly used to determine bending stresses in lumber beams, it should be kept in mind that they are based on the assumption that the material behaves elastically (Fig. 5.12). The maximum bending stress so computed is also called the *modulus of rupture* (MOR), which is a measure of the tensile or the compressive capacity of the material, depending on the type of failure.

But lumber does not exhibit truly elastic behavior up to failure. Although the stress-strain diagram is linear at small loads, the latter part of the diagram represents

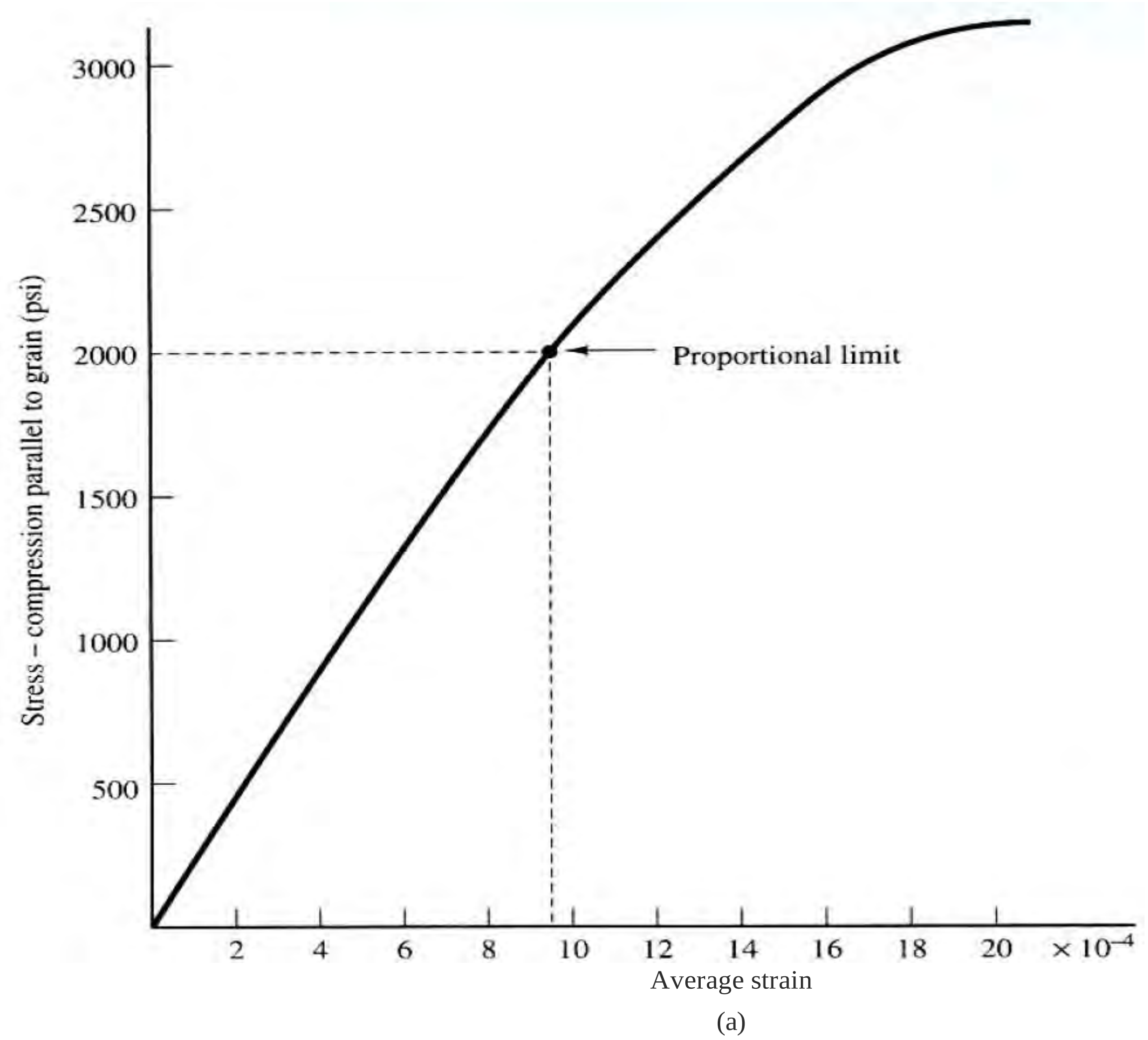
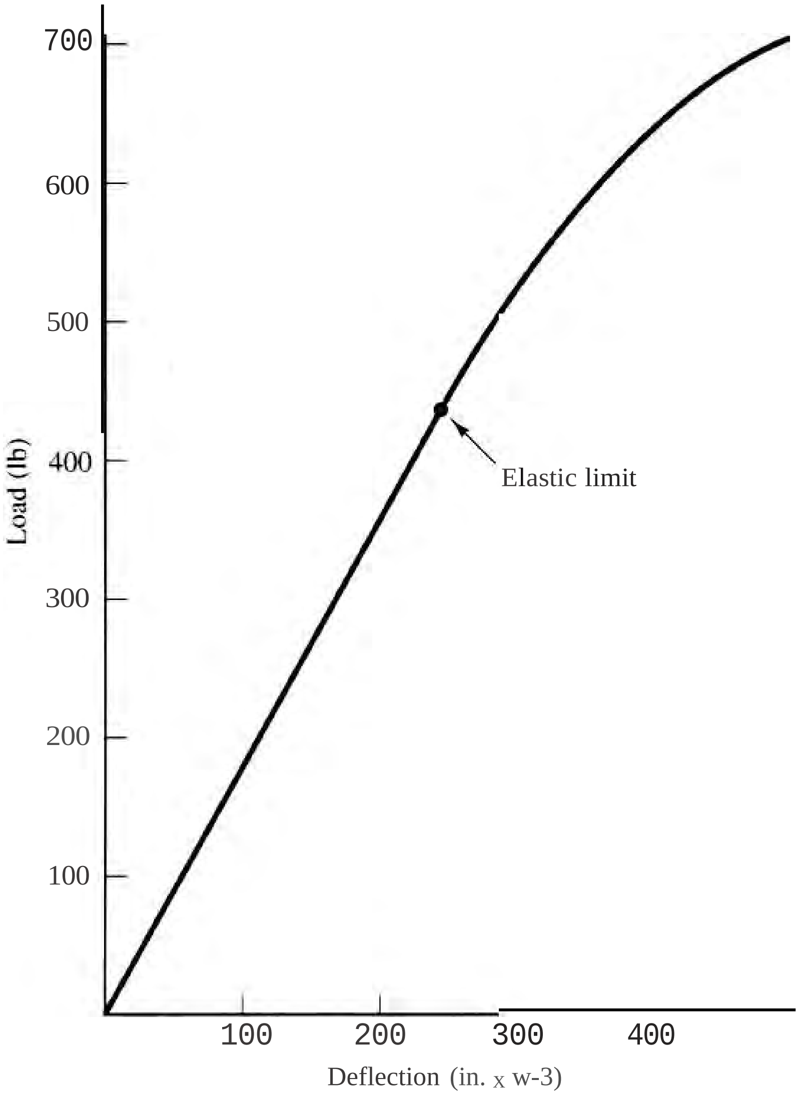


Figure 5.12a Typical stress-strain diagram of lumber (compression parallel to grain).

inelastic behavior (Fig. 5.12). Because of this the MOR value calculated from the flexural formula is intermediate between the tensile and compressive strengths of wood and does not truly represent the extreme fiber stress. The discrepancy between the actual unit stress and the calculated stress (using the flexural formula) is thus due to inelastic behavior and also to the shifting of the neutral axis. It should thus be emphasized that although MOR and flexural formula are used to calculate bending properties of lumber, these measurements are not a valuable index of the quality of wood.

Failure of lumber beams is generally characterized by wrinkling or crushing of fibers in the compression zone, followed by a final failure marked by splitting or snapping of fibers in the tension zone. Green lumber exhibits compression failure (with or without tension failure), whereas dry lumber generally fails suddenly in tension accompanied by a loud noise.

The MOR value of most softwoods (clear wood) is greater than 6000 psi (41.3 MPa) (Table 5.6). The higher the specific gravity and the lower the moisture content, the larger is the MOR value. For example, Douglas Fir, with a specific gravity of about



(b)

Figure 5.12b Typical load deflection diagram for 2 X 2-in. clear wood beam.

0.48 (at 12% moisture content) has a MOR value of about 12,500 psi (86.1 MPa), whereas Eastern Hemlock, with a specific gravity of 0.4 (at 12% moisture content) has a MOR value of about 9000 psi (62 MPa). When the moisture content increases to about 20% the corresponding values are 7700 and 6400 psi (53 and 44 MPa), respectively (Fig. 5.13).

Hardwoods generally have higher bending strengths than those of most softwoods. Black Locust, Hickory, and White Oak are some of the strong hardwoods (in bending), and Longleaf Pine, Douglas Fir, and Tamarack are some of the strong softwoods.

Tensile strength. When a clear wood specimen is subjected to tensile forces parallel to the grain, it is found to have the greatest of all strength characteristics. *Tensile strength* parallel to the grain is about two to four times the compressive strength parallel to the grain (Table 5.6). Failure in a tension specimen is characterized by transverse rupturing of the cell walls. Knots greatly reduce the tensile strength (both parallel and perpendicular to grain), which, however, seems to be less affected by the moisture content than are other mechanical properties.

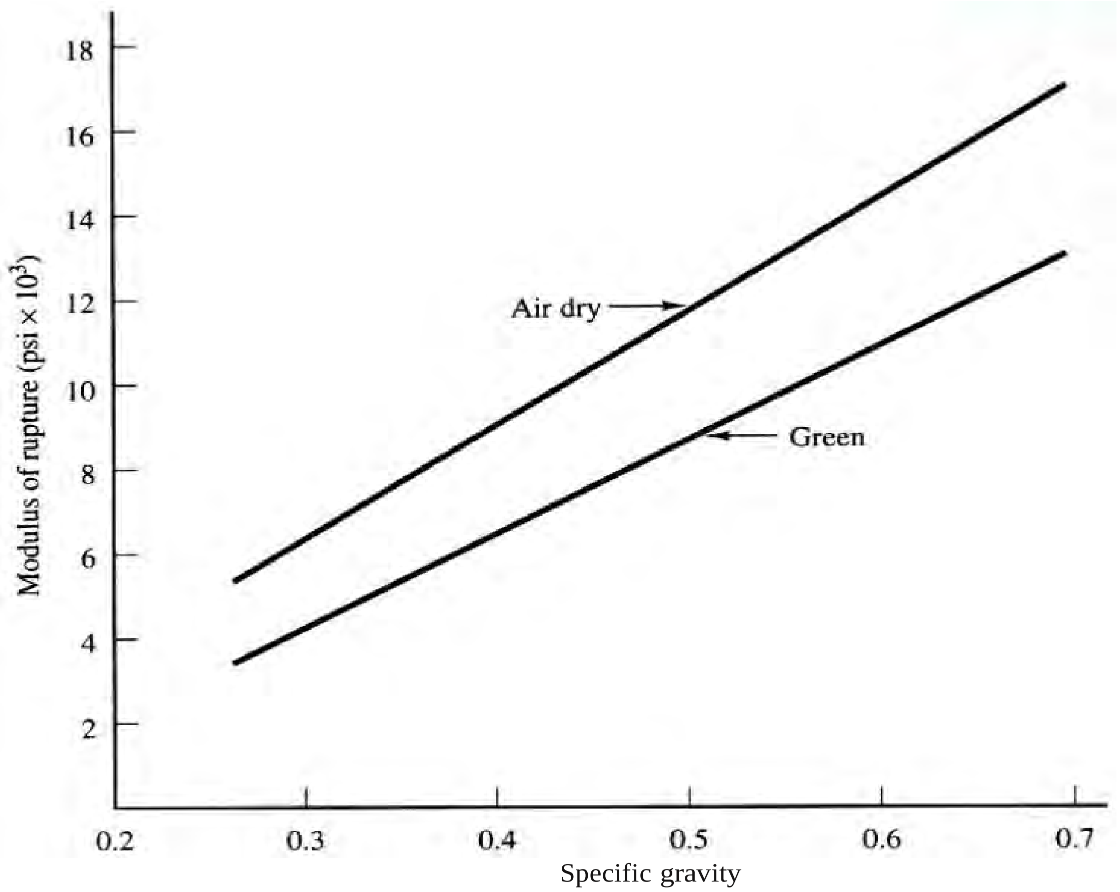


Figure 5.13 Increase in bending strength with increase in specific gravity (average values obtained for a large number of hardwoods and softwoods).

The tensile strength of wood perpendicular to the grain is very small. Failure is characterized by separation of cells and fibers in longitudinal planes. Defects such as knots, shakes, and checks reduce further tensile strength perpendicular to the grain. The tensile strength of clear softwoods, perpendicular to the grain, varies between 180 and 450 psi, whereas that of strong hardwoods is higher than 500 psi. Since these values are very low, the allowable tension value perpendicular to the grain in ordinary lumber is taken as zero; loads that cause tensile stresses perpendicular to the grain should not be applied to lumber.

Shear strength. A flexural member is always subjected to shear forces. The resulting horizontal shear stress at the neutral axis of a wood beam may cause shear failure. The shear strength of lumber is small, generally in the range 700 to 1500 psi (4.8 to 10.3 MPa). Most hardwoods have higher shear strengths than those of most softwoods. Defects such as knots and shakes decrease the area under shear, and the calculated shear strength of lumber with these defects is lower than that of clear wood.

Summarizing the discussion above, mechanical properties of lumber are affected significantly by two properties:

- Moisture content
- Specific gravity

Most mechanical properties increase linearly with specific gravity and decrease with increase in moisture content. Beyond the fiber saturation point, the mechanical properties remain independent of changes in moisture content. Knots weaken the lumber, and most mechanical properties are lower at sections containing knots than in clear wood. Knots displace the clear wood and wood grain. This discontinuity of wood fibers leads to stress concentration and checking often occurs around knots during the drying operation. The effects of knots are more on axial tensile strength, less on bending strength, and very little on axial compressive strength.

5.7.1 Effect of Slope of Grain

The term *slope of grain*, defined earlier, refers to the angle between the direction of fibers and the direction of the edge of a piece of lumber. Wood has different properties in two directions: parallel to grain and perpendicular to grain. Strength properties in any direction between parallel to grain and perpendicular to grain directions can be approximated using a *Hankinson-type formula*. The strength of wood at an angle ϕ to the fiber direction can be found as

$$N = \frac{PQ}{P\sin^n\phi + Q\cos^n\phi}$$

or

$$N = \frac{P}{(P/Q)\sin^n\phi + \cos^n\phi}$$

where N is the strength property at an angle ϕ to the fiber direction, Q the strength perpedicular to the grain, P the strength parallel to the grain, and n an empirical constant, the value of which depends on the type of stress (or load). For example, the value of n ranges between 1.5 and 2 for tensile strength and bending strength (Table 5.7). Note that the ratio *QIP* gives the relative strength value between perpendicular and parallel to grain and generally lies between 0.04 and 0.1 for most loads.

5.7.2 Strength Ratio and In-grade Testing

All structural lumber is stress graded, which establishes a grade stamp for every piece of lumber. The hypothetical strength properties of lumber belonging to any stress grade of an

TABLE 5.7 EFFECT OF GRAIN ORIENTATION ON STRENGTH PROPERTIES

Property	n	*QIP*	Comments
Tensile strength	1.5-2	0.04-0.07	
Compressive strength	2-2.5	0.03-0.4	n is generally taken as 2.0
Modulus of elasticity	2	0.04-0.12	
Bending strength	1.5-2	0.04-0.1	n is generally. taken as 0.5

individual species (i.e., lumber with some measurable defects) are determined from the measured mechanical properties of clear wood specimens of that species, followed by the application of a limiting factor called the strength ratio. The strength properties so derived are adjusted further to include a safety factor and compensate for duration of load and other service-related factors, which then provides the allowable (design) properties of this grade.

All allowable properties of lumber belonging to Beams and Stringers and Posts and Timbers categories given in current design standards have been derived from results of tests done on small clear specimens. A comprehensive reevaluation of the mechanical properties based on tests done on full-sized members-termed an *in-grade testing* program-is the basis of recommended allowable properties of lumber belonging to the Dimension category.

The strength properties of lumber, such as **MOR,** compressive strength parallel to grain, and modulus of elasticity, were discussed earlier. The *strength ratio* is the hypothetical ratio of the strength of a piece of lumber with visible strength-reducing growth characteristics to its strength if those characteristics were absent. The true strength ratio of a piece of lumber is never known and can only be estimated. The assigned strength ratio (to a defect), ranging from 0 to 100%, serves as a predictor of lumber strength.

For example, to account for the weakening effect of knots, a knot is treated as a hole that reduces the cross section of lumber. In a beam containing an edge knot, the strength ratio is equal to the ratio of the MOR value of the beam with reduced cross section to that of the full beam (Fig. 5.14). This can be calculated from the flexural formula as

$$\text{strength ratio} = \left(\frac{h-k}{h}\right)^2$$
$$= \left(1-\frac{k}{h}\right)^2$$

where k is the height of the knot and h is the beam depth.

The strength ratio for all knots, shakes, checks, and splits are derived using concepts similar to the one discussed above and are given in ASTM D245. When several characteristics are present that reduce the strength properties, only the characteristic that gives the lowest strength ratio is used to derive the estimated strength of that piece of lumber.

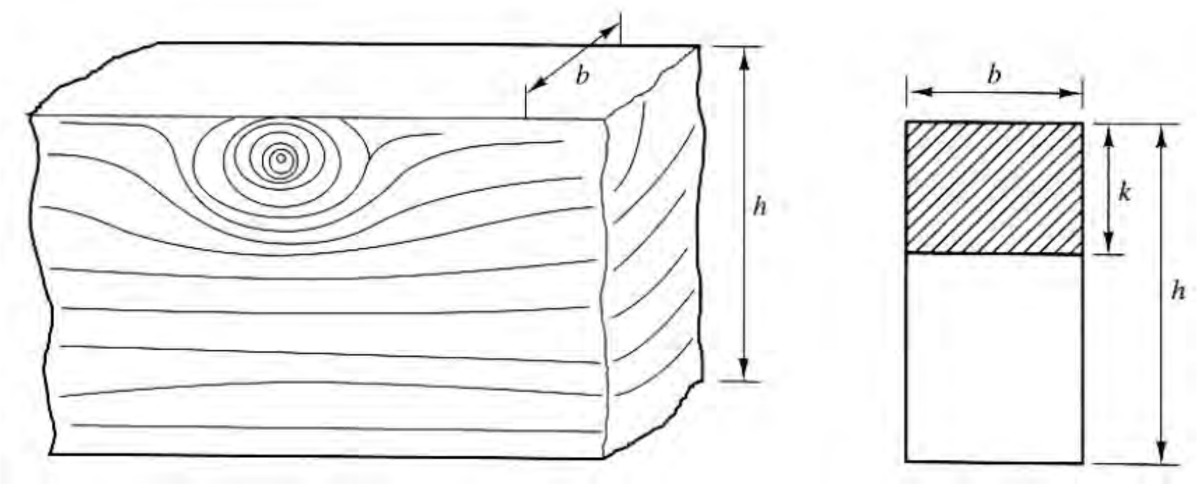


Figure 5.14 Edge knot in beam.

To account for the variations between pieces of lumber in each grade, the strength ratio is applied to a near-minimum clear strength value. As mentioned earlier, the allowable value in each grade is then obtained by adjusting this assumed strength value of the grade to account for the safety factor, duration of load, and other factors. These allowable properties are listed in the National Design Specifications for Wood Construction.

5.7.3 Examples

Example 5.3

Find the size classification of the following lumber:

(a) Nominal 2 x 4
(b) Nominal 2 x 8
(c) Nominal 4 x 16
(d) Nominal 6 x 6
(e) Nominal 6 x 16

Solution: (Refer to Table 5.5.)

(a) Size 2 x 4: thickness not larger than 4 in.; Dimension
(b) Size 2 x 8: thickness not larger than 4 in.; Dimension
(c) Size 4 x 16: thickness not larger than 4 in.; Dimension
(d) Size 6 x 6: thickness larger than 4 in.; square; Post and Timber
(e) Size 6 x 16: thickness larger than 4 in.; rectangular; Beams and Stringers

Example 5.4

Find the cross-sectional properties of 4 x 16 nominal-size lumber header beam.

Solution: (Refer to Table 5.4.)

Nominal size: 4 x 16
Dressed size: 3.5 x 15.25

$$\text{Cross-sectional area} = 3.5 \times 15.25 = 53.4 \text{ in}^2$$

$$\text{Moment of inertia} = \frac{3.5 \times (15.25)^3}{12}$$

$$= 1034.4 \text{ in}^2$$

$$\text{Section modulus} = \frac{1034.4}{15.25} \times 2$$

$$= 135.7 \text{ in}^2$$

E,.-ample S.S

Determine the cross-sectional properties of glulam beam built with six laminations of 2 x 6 Douglas-Fir lumber.

Solution:

Number of laminations = 6

Width of beam (Table 5.8) = 5.125 in.

TABLE 5.8 WIDTH OF GLULAM MEMBERS

Nominal width of laminating lumber (in.)	Net finished width of glulam (in.)	
	Southern Pine	Western species
3		2.25
4	3	3.125
6	5	5.125
8	6.75	6.75
10	8.5	8.75
12	10.5	10.75

$$\text{Beam height} = 6 \times 1.5 = 9 \text{ in.}$$

$$\text{Cross-sectional area} = 5.125 \times 9$$

$$= 46.1 \text{ in}^2$$

$$\text{Moment of inertia} = \frac{5.125 \times (9)^3}{12}$$

$$= 311.3 \text{ in}^4$$

Example 5.6

In a piece of lumber the slope of the grain is measured as I in 20. Assuming the perpendicular-to-parallel strength ratio to be 0.1 and using a value of 1.5 for *n*, determine the strength of the lumber.

Solution: For a slope of 1 in 20,

$$0 = 2.86$$

$$\tan 0 = 0.05$$

$$\sin 0 = 0.05$$

$$\cos 0 = 0.998$$

$$Q/P = 0.1$$

$$\text{Strength of lumber} = \frac{P}{\dfrac{\text{Sin}^{1.5}\phi}{0.1} + \cos^{1.5}\phi}$$

$$\frac{P}{\dfrac{0.05^{1.5}}{0.1} + (0.998)^{1.5}}$$

where P is the strength parallel to grain. Thus there is a 10% reduction due to a slope of grain of 1 in 20.

Example 5.7

For a knot of depth equal to one-fourth the depth of the beam, estimate the **MOR** value if that of clear wood is 10,000 psi.

Solution: The strength ratio for $k/h = 0.25$ is

$$(1 - 0.25)^2 = 0.5625$$

If the clear wood strength **(MOR)** is equal to 10,000 psi,

$$\text{estimated strength of lumber} = 0.5625(110{,}000) = 5625 \text{ psi}$$

5.8 WOOD PRODUCTS

Although the tractional application of wood is in the form of lumber, a large number of wood products have come into the market in recent years and are being used extensively in construction. The most common wood products are glulam (which stands for "glue-laminated timber"), panel products, and manufactured structural components (Fig. 5.15). Properties and applications of glulam are discussed in the following section. Manufactured structural components are those built using lumber and panel products (other than glulam). These are described briefly in Section 5.8.4. General features of panel products are explained below, but some special characteristics are described in Sections 5.8.2 and 5.8.3.

Panel products. There are two types of panels: veneered panels and nonveneered panels. *Veneered panels,* also called plywood, are made from thin sheets of wood, whereas *nonvenereal panels* are manufactured from wood particles or fibers. Both types of panels are used for structural applications such as floor panels and wall panels, and for nonstructural applications such as in furniture and cabinets. These panel materials have also been used as web material of built-up wood I beams (because of their outstanding shear characteristics). Structural applications of nonveneered panels have become more common since around 1980. Nonveneered panels are divided into two major categories:

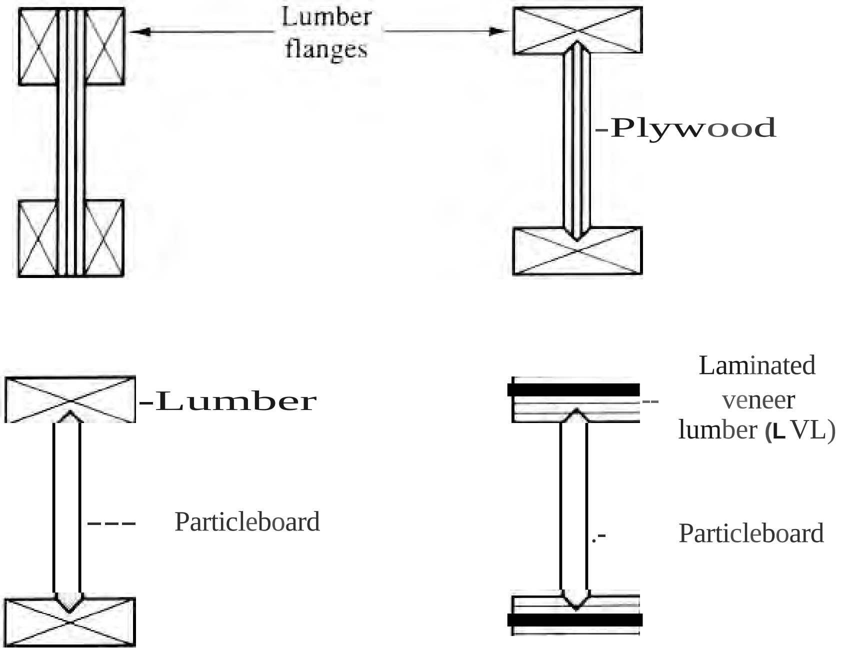


Figure 5.15 Manufactured I beams.

- Particleboards
- Fiberboards

Particleboard is a generic term that identifies various types of panels manufactured from discrete pieces of wood particles, as distinguished from fibers, combined with a synthetic resin or glue, and bonded together under heat and pressure in a bot press in which an entire interparticle bond is created. It is classified into three types: *low-density particleboard* (density less than 37 pcf (590 kg/m^3) and specific gravity 0.59), *medium-density particleboard* (density between 37 and 50 pcf (590 and 800 kg/m^3) and specific gravity between 0.59 and 0.80), and *high-density particleboard* which has a density greater than 50 pcf (800 kg/m^3) (specific gravity 0.80).

Fiberboard is a generic term for a homogeneous panel made from wood fibers (as opposed to particles) that has not been consolidated under heat and pressure as a separate stage in manufacture. Fiberboard panels have a density between 10 and 31 pcf (160 and 500 kg/m^3) (specific gravity between 0.16 and 0.50). In Sections 5.8.3 and 5.8.4 we describe manufacturing details, properties, and applications of these panel products.

5.8.1 Glulam

Glulam or glue-laminated timber, introduced in Europe in the late nineteenth century, consists of sawn lumber laminations bonded with an adhesive so that the grain of all laminations runs parallel with the long direction (Fig. 5.16). One of the early uses of glulam in the United States was a glulam arch erected in 1934 at the USDA Forest Products Lab in Madison, Wisconsin. Glulam is now manufactured to follow the Standard *ANSU*AITC A190.l-1993, and developed and sold as a structural product. (ANSI is the American National Standards Institute, and AITC the American Institute of Timber Construction.)

Glulam can be manufactured in a variety of shapes and sizes. Curved, tapered, circular, and spiral-shaped members have been used (Fig. 5.17). Curved arches have been used to span more than 300 ft (91 m). Glulam domes exceeding 500 ft (152 m) have been built.

Glulam is manufactured using lumber with nominal thicknesses of 1 and 2 in. (¾ and 1½ in. dressed sizes). The "1 x" lumber is generally used to form curved members and the "2 x" lumber to manufacture straight members. Straight beams can be designed

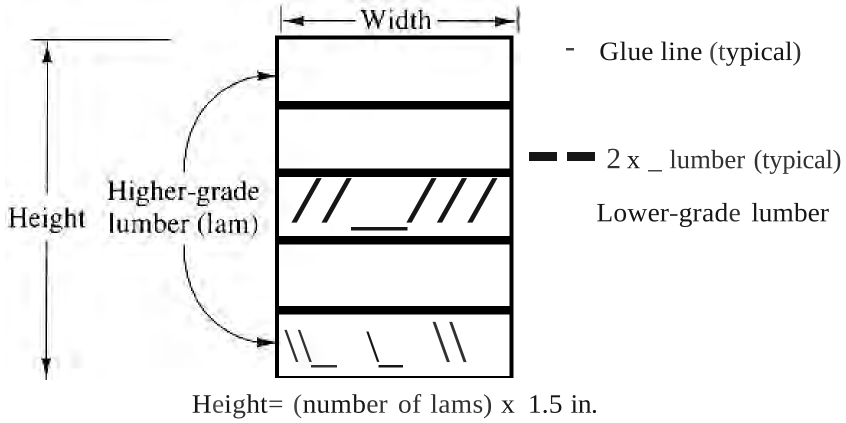


Figure 5.16 Cross section of glulam.

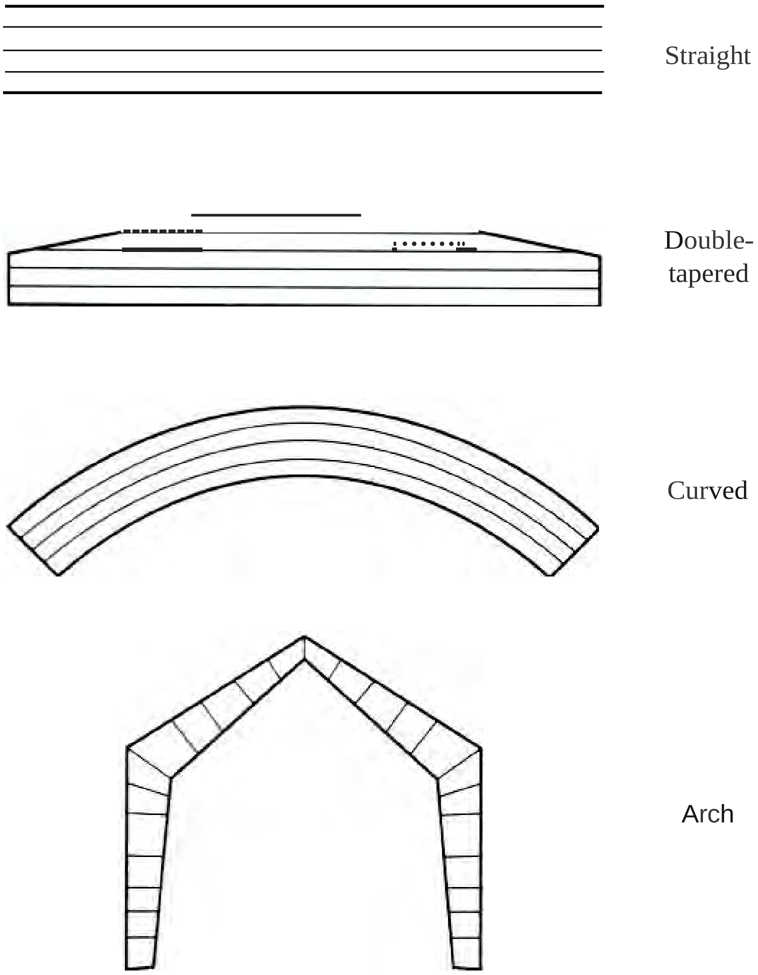


Figure 5.17 Shapes of glulam.

and manufactured with horizontal laminations (load applied perpendicular to the wide face of laminations) or vertical laminations (load applied parallel to wide face of laminations) (Fig. 5.18). Glulam can be fabricated in various widths as shown in Table 5.8.

Glulam is normally manufactured using lumber with the moisture content in the range 10 to 16%. It generally comes with camber or upward deflection. When manufactured with a moisture content of less than 12% and used under conditions where the moisture content is less than I 2%, glulam is practically free from shrinkage and swelling. *Dry condition* is assumed when the moisture content during service does not exceed 16%. *Wet use condition* is assumed when the moisture content during service exceeds 16%. However, note that glulam is seldom used in wet condition.

The strength characteristics of glulam are stronger in the longitudinal direction and weaker in the transverse direction. Manufacturers place high-grade lumber near the surface (top and bottom) and use low-grade lumber for the center (near the neutral plane). All joints (between lumber pieces in a lamination) must be of the scarf or at least of the finger type. Strength-reducing joints and knots are staggered.

Laminating allows control over the location of material of different quality within the member cross section. By placing the strongest material in the regions of greatest stresses (near the top and bottom in the case of a flexural member), member performance can be improved. Laminating also allows the dispersion of lumber defects throughout the length of the member (Fig. 5.19).

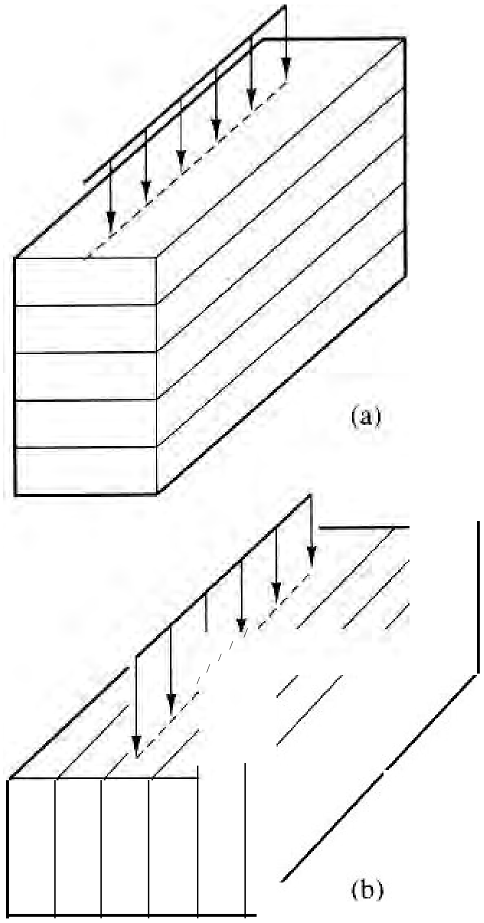


Figure 5.18 Loading direction: (a) loaded perpendicular to wide face of laminations. (b) loaded parallel to wide face of laminations.

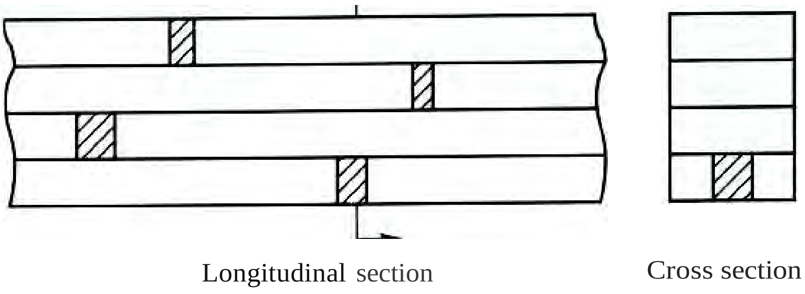


Figure 5.19 Staggered knots in glulam.

Glulam is commonly used as a replacement for sawn lumber when higher-sized lumber is unavailable. In practice, sawn lumber beams of nominal size greater than 6 x LS (length over 25 ft) are difficult to obtain. In these situations, glulam or other prefabricated members can be used. There are additional advantages that come with the use of glulam. Allowable strength properties of glulam are generally superior to those of sawn lumber. Glulam is a dimensionally stable material with average moisture content of 12%, compared with about 30% for sawn lumber (green). Adhesives used in glulam are not combustible and they do not lose strength under heat. Because of all these, glulam is commonly used as purlins, joists, headers, beams, and truss members. It is also used in the design of pedestrian and highway bridges.

5.8.2 Plywood

Plywood is a panel product with an odd number of layers of veneers or plies, glued together so that the grains of adjacent layers are perpendicular to one another. Outer layers and all odd-numbered layers generally have the grain direction oriented parallel to the long direction of the panel (Fig. 5.20). Plywood comes in a common size of 4 x 8 ft.

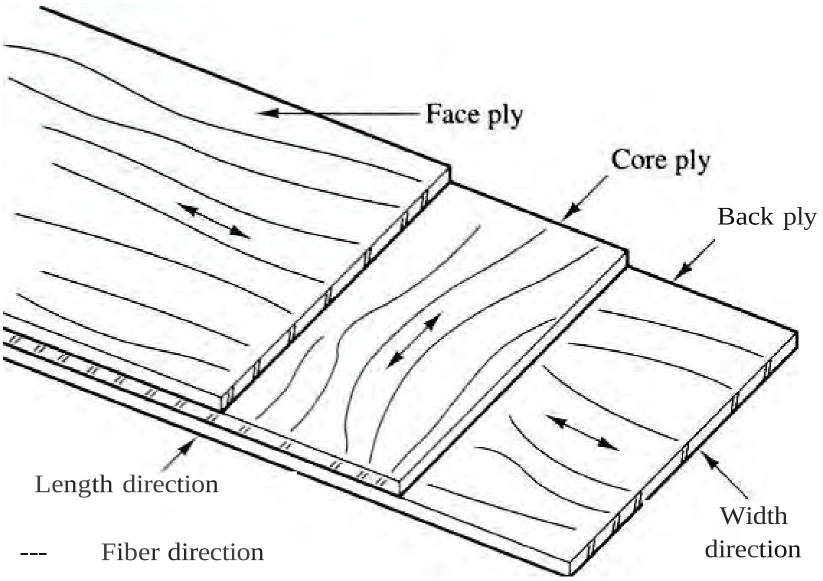
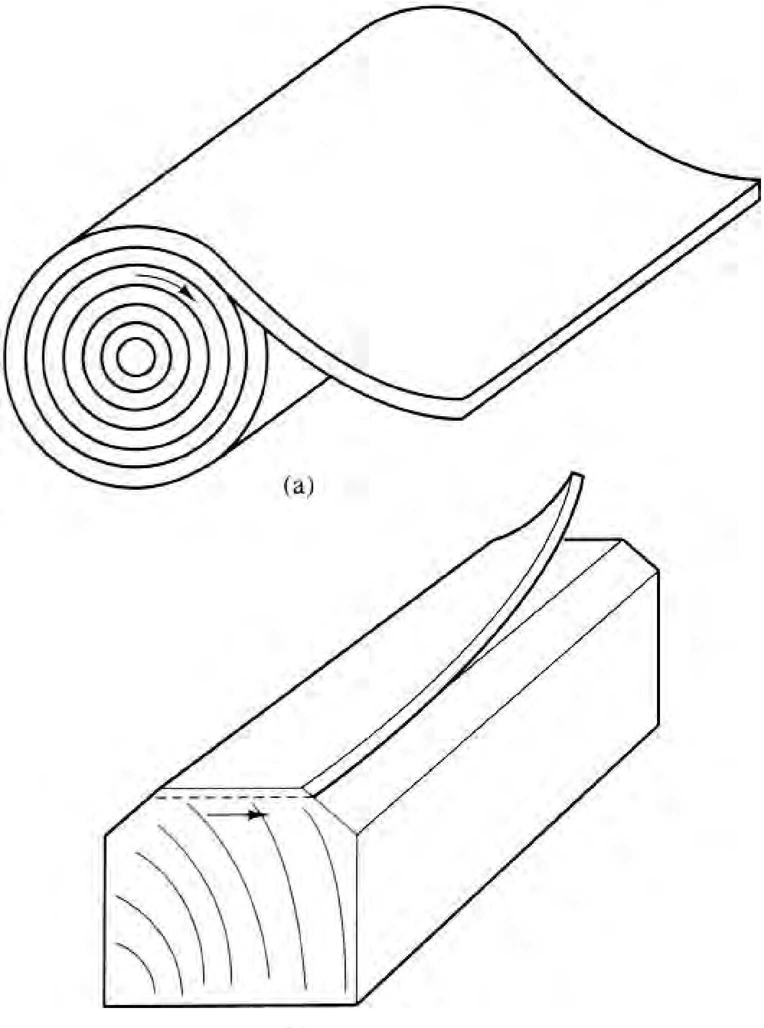


Figure 5.20 Plywood construction.

A *veneer* (or *ply)* is a thin sheet of wood, peeled from a log, from which the plywood is made (Fig. 5.21). Early evidence of the practice of veneering comes from mural paintings on walls of tombs in Egypt. The art of overlaying and inlaying woodwork with


(a)

(b)

Figure 5.21 Veneer production: (a) rotary cutting: (b) slicing.

decorative veneers from rare and imported wood was well established in Egypt around 2000 s.c. Up to about 150 years ago, veneers were usually applied to a solid base.

Veneers. Nowadays, again to conserve timber and the dwindling supply of good-quality wood, the base for the outer veneers is itself made up of several layers of wood, placed one upon the other, such that the direction of the grain in each ply alternates in direction at right angles. Ordinarily, no single ply or veneer will exceed 7'16 in. (7.9 mm) in thickness. Plywood *core* refers to all plies or layers between the face ply and the back ply.

Veneers are manufactured in various grades, depending on defects such as knots, holes, discoloration, and grain orientation. Grades N and A are the highest grade, and grade D is the lowest grade. Grade N has a smooth surface with a natural finish and is free of natural defects. Grade A has smooth paintable surface and a limited number of repairs. Grade B has a large number of patches or repairs and minor splits. Grade C, often used as the face on flooring and ceiling sheets, has knot holes and other defects. When these defects have been repaired, patched, or plugged, the grade becomes C-plugged. Grade D, which is commonly used as the back face and core of higher-grade plywood, has much larger knot holes and splits. It is used primarily in the production of interior-grade plywood. The durability characteristics of the species from which the veneers are produced should also be considered in the selection of a veneer for plywood.

Manufacture. The plywood industry dates back to about I 905, and World War II greatly accelerated the plywood technology (for use in small naval military aircraft). The manufacture of plywood involves placing heated lumber blocks (or bolts) into a lathe, peeling the blocks, clipping the resulting sheets to size, and stacking the clipped sheets. (Note that prior heating-steaming or soaking in hot water-softens the wood and the knots, making it easier to peel or cut.) These sheets are then dried to a target moisture content (2 to 4% moisture content). Adhesives are applied on individual sheets and panels are assembled. The panels are first consolidated on a cold press and later loaded into a hot press, where heat and pressure (as high as 200 psi or 1.4 MPa) are applied on the panels. These panels are then set aside for the adhesive to cure, following which they are trimmed. After sanding and patching, the panels are strapped in bundles for shipping.

Virtually all plywood manufactured in the United States is bonded using phenol-formaldehyde (PF) or urea-formaldehyde (UF) adhesive. Softwood plywood for interior and exterior applications (interior grade or interior type, and exterior grade or exterior type), and exterior-grade hardwood plywood are manufactured using **PF** adhesive. *Interior-grade hardwood plywood* is manufactured with UF adhesive.

Plywood is manufactured seasoned. Drying of veneers is essential to hot-press gluing. Gluing adds about 5% extra moisture. After manufacture, plywood has only about 6 to 10% moisture. Any subsequent moisture absorption can cause it to warp and buckle. Like all wood materials, plywood (and other panel products) picks up and loses moisture with changes in the environmental humidity. These changes in moisture content lead to dimensional changes: linear and thickness swelling and shrinkage. Changes in size lead to altered strength and stiffness and affect the performance under load. Generally, dimensional changes at relative humidity below 80% are insignificant. Above this relative humidity, properties decrease rapidly.

Types. Plywood is divided into two types, based on the type of wood used:

- Softwood plywood
- Hardwood plywood

Softwood plywood is manufactured using softwood logs, most commonly Douglas Fir and Southern Pine. It is used principally as a construction material, as floor panels, roof panels, wall sheathing, siding, and concrete forms, and in manufactured structural components. Most of the softwood plywood (also called structural plywood) produced in the U.S. is manufactured to meet the requirements of United States Products Standard PS 1-83 for Construction and Industrial Plywood (Fig. 5.22). *Hardwood plywood*, which is manufactured from a variety of hardwood logs, such as oak, maple, and birch, is principally used for paneling, industrial parts, and furniture.

Plywood is manufactured in three exposure classification classes:

- Exterior type
- Interior type
- Exposure-1 type

Exterior plywood has exterior glue and the lowest veneer grade is C. *Interior* plywood is manufactured using interior glue and includes D-grade veneer. When interior plywood is manufactured with exterior glue, it is called *Exposure-I* plywood. (Note that grade A is the highest veneer grade, and grade D is the lowest veneer grade.)

Softwood plywood (and other structural panels) have a grade stamp that shows the span rating for the panel. The *span rating* (Fig. 5.22) consists of two numbers arranged as a fraction. The larger number is the allowable span length when used as roof sheathing, and the smaller number is the allowable span length when used as a floor panel. In some panels the span rating is given as a single number, which is the spacing of floor supports.

A strip of structural plywood placed between supports will not carry more load than a piece of softwood lumber of the same width and thickness as the plywood. However, plywood has strength in bending in either direction, and hence it will serve to carry the floor load whether laid parallel or perpendicular to the floor joists. But for the most efficient use of plywood, it should be placed with the face grain perpendicular to the joists. In addition, plywood comes in a 4 x 8 ft size (J .2 x 2.4 m), which makes it impossible to deform the plane by a force applied parallel to the plane. Thus plywood and similar panel products are excellent for use as wall and roof sheathing as well as wall siding.

5.8.3 Other Panel Products

Nonveneered panel products are divided into two categories:

- Particleboard
- Fiberboard

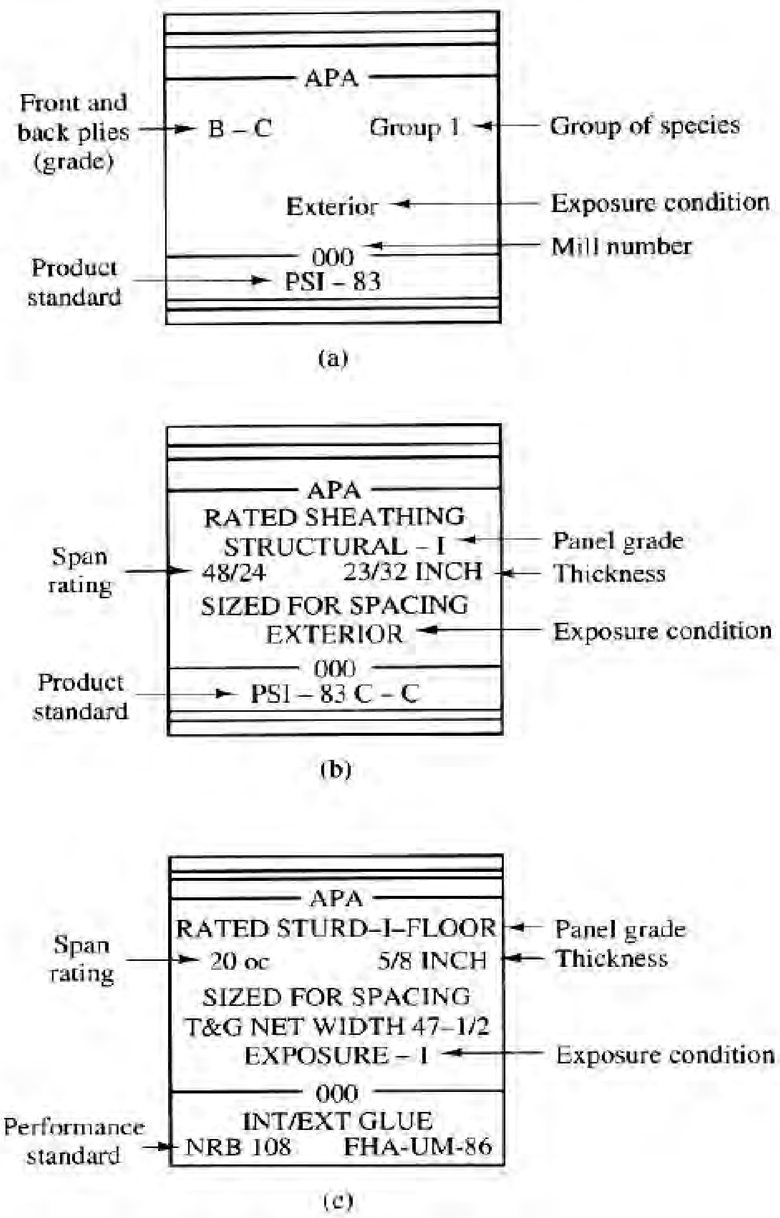


Figure 5.22 Panel grades:

(a) nonstructural panel, veneered;
(b) structural panel, veneered; (c) structural panel, nonveneered.

Particleboard. Particleboard is made from small particles of wood and is sometimes called chipboard, flakeboard, splinter board, waferboard, strand board, and oriented strand board depending on the particles and their orientation. *Particles* are pieces of wood smaller than veneer sheets but larger than wood fiber. The raw material for the manufacture of particles comes from many sources, such as plywood mill waste, sawdust, roundwood (round logs), planer shavings, and wood residue (such as broken logs and branches). Residues from the milling operation are commonly used as particles.

The manufacturing stages involve forming the particles by cutting the wood chips, drying to about 2 to 5% moisture content, and removal of fines, followed by the addition of resin or glue. This mixture is formed into a low-density mat which is compressed, heated, and cured. These boards are cooled prior to stacking, and most are sanded before shipping.

The most common resin used in the manufacture of particleboard is urea-formaldehyde (UF), and these boards should be used for inside applications only. Waferboard and oriented strand board are manufactured with phenol-formaldehyde (PF) and can be used for interior or exterior applications. These two types of panels (oriented strandboard and waferboard) come under a common category called flakeboard.

Flakeboard, introduced in the 1950s, identifies a panel manufactured from specially produced flakes, generally from low-density or low-quality species such as aspen and pine. Waferboard is produced exclusively from aspen. *Wood wool (excelsior)* is long curly slender strands of wood used as an aggregate component for some particleboard-called excelsior board.

Properties of particleboard depend on its density; most have an average density of 40 to 50 pcf. When used as a raw material, hickory (which has a specific gravity of 0.72) generates particleboard having a density of about 64 pcf, whereas Douglas Fir (which bas a specific gravity of 0.48) produces particleboard of density 43 pcf. Boards made from dense woods become very heavy and difficult to handle and ship. Therefore, as a general rule, lower-density woods are preferred.

More than one-half of particleboard manufactured in the United States goes into the manufacture of furniture and cabinets (as architectural veneered panels). Some particleboards are also used as underlayment (the layer below the floor covering) and in mobile homes. Flakeboard (oriented strandboard and waferboard) is used primarily in engineered construction as replacement for plywood.

Waferboard and strand board. As discussed earlier, the term *flakeboard* refers to a panel produced with flakes. Flakes are small wood particles, resembling a small piece of veneer, with fiber direction essentially in the plane of the flake. They are a little thinner than wafers (0.25 to 0.5 mm) and somewhat longer than they are wide. *Waferboard* is a panel made from wood wafers. A wood wafer is a nearly rectangular particle of wood of thickness in the range 0.5 to I mm and length of at least 30 mm (l 1/i6 in.). Waferboard has nearly equal properties in all directions parallel to the plane of the panel.

Strand board is made using wood strands which are similar to wafers except that they have even a larger length to width ratio (about 2:I). *Oriented strand board* (OSB) is usually made in three layers, with strands alternating 90° in orientation. Alignment of strands is done by means of an electrical field, or mechanically by vibrating the particles through fins. The alignment of strands makes this panel stronger and stiffer than waferboard.

All flakeboards (strandboard, oriented strandboard, and waferboard) have made major inroads into the construction industry, due primarily to lower cost, thanks to low-quality wood species, which otherwise have no appreciable structural properties. The use of exterior glue and the elaborate laboratory testing program of the American Plywood Association and others have made it possible to use a span rating stamp, similar to that on structural plywood, on these panels. As a result, oriented strand board and waferboard are being widely accepted as substitutes for softwood plywood in building construction. They are used as roof sheathing, floor sheathing, siding, and in other light residential applications.

Waferboard bas a modulus of rupture between 2500 and 3000 psi (17.2 and 20.7 MPa) (Table 5.9) and a modulus of elasticity around 500,000 psi (3.5 x 10^3 MPa). It is not as stable as plywood. The lack of alignment of fibers in waferboard is the reason for its low bending properties. The swelling of particleboard, in general, is higher than that of solid wood of the same thickness. Mechanical properties of OSB are nearly the same as plywood.

Fiberboard. Fiberboard (or reconstituted wood board) comes in two types:

- Hardboard
- Medium-density fiberboard

Fibers are slender threadlike elements (of length less than ½ in. (8.5 mm) but generally of ½s in. (1 mm) or a group of wood fibers resulting from chemical or mechanical defiberization, or both. A number of raw materials, such as coarse residues from other forest products, bagasse (fiber residue from sugarcane), wastepaper, and pulp chips, can be used in the manufacture of fibers. These raw materials are broken down into fibers through thermal-mechanical treatment. Then the fibers are interfelted under controlled conditions of hot pressing. This will cause rebonding of the lignin, which in addition to the binding agents added (e.g., synthetic and natural resins, paraffin, and asphalt) will produce a bonded panel product.

Hardboard has a specific gravity in the range 0.5 to 1.45 [density of 31 to 90 pcf (500 to 1450 kg/m^3)), and medium-density fiberboard has a specific gravity of 0.5 to 0.88 [density of 31 to 55 pcf (500 to 880 kg/m^3)]. In addition to these two types, fibers are also used in the manufacture of insulation board and laminated paperboard.

Medium-density fiberboard and hardboard. *Medium-density fiberboard* (MDF), developed in the 1960s, is similar to hardboard and particleboard and has a density in the range 31 to 55 pcf (500 to 880 kg/m^3). Early steps in the manufacture of MDF are similar to those of hardboard. Logs are reduced to chips, thermomechanically pulped,

TABLE 5.9 AVERAGE BENDING PROPERTIES OF PANEL PRODUCTS

Panel	Modulus of elasticity (psi)	Modulus of rupture (psi)
Plywood (parallel to face grain)	1.25 X 10^6	6500
Waferboard	0.5 X 10^6	3050
Oriented strandboard (parallel to face strand)	1.25X 10^6	7000

dried, and blended with resin (and occasionally, wax). The amount of resin used is much higher than that for hardboard. The mixture is formed into a mat that is subsequently pressed to the desired thickness and density.

MDF has more uniform density and a smoother edge than those of particleboard. It is used primarily in the furniture industry, replacing solid wood, plywood, and particleboard. It is also tried in the manufacture of doors, moldings, and other elements. Its smooth surface facilitates wood-grain printing and veneering.

Hardboard (also called gainless wood), developed in 1924, is a medium- to high-density wood fiber product that has a specific gravity closer to 1.0. It is manufactured in sheets of thickness in the range ½6 to ½ in. (0.16 to 1.27 mm) and can be molded into a variety of shapes. Like MDF, it is also produced from mechanically produced pulp (by thermomechanical process). Note that when the wood chips are fiberized, lignin is not dissolved, and the attrition mill, which is like a grinding machine, rubs the fibers apart. The resulting pulp contains fine fibers, bundles of fibers, and larger fiber aggregates. After drying, fibers are formed into a mat and pressed using either water (wet process) or air (dry process). Heat and pressure reactivate lignin as a binder, which makes the boards stronger.

Hardboard contains almost no moisture as it leaves the press. Its modulus of rupture varies between 2000 and 7000 psi (13.8 and 48.2 MPa), and tensile strength (parallel to surface) ranges between 1000 and 3500 psi (6.9 and 24.2 MPa). Because it is denser, it is also harder than natural wood. Its grainless character gives equal strength characteristics in all directions. As it contains lignin, with changes in moisture content it shrinks and swells just like wood. Hardboard is used in the manufacture of furniture, cabinets, and exterior siding. It is also used as floor underlayment and as concrete formwork. High-density hardboard is also used as a web member of manufactured I beams.

5.8.4 Manufactured Components

In addition to panel products and glulam, discussed earlier, wood is used in the manufacture of a number of prefabricated building components, such as I beams, manufactured trusses (trussed rafters), composite panel (comply), composite wood I beams, and laminated veneer lumber. Most of these are proprietary products, and one should refer to the manufacturer's literature to understand their properties.

Composite panel or *COM-PLY* is a panel consisting of veneers and other wood-based materials. It was introduced into the market around 1975 and is made with face veneers bonded to a core layer of oriented strandboard or other particleboard. It can also be manufactured with lumber core. Composite panel is interchangeable with similar-grade plywood.

Composite wood I beams are made with lumber or laminated boards for top and bottom flanges, and plywood or flakeboard as webs (Fig. 5.15). They are gaining popularity where long-span support is required. Hardboard webbed I beams have been in use in Sweden for more than 50 years. In the United States, plywood is commonly used for webs. Oriented strand board and waferboard are also used.

Laminated veneer lumber, or *LVL,* also called *parallel laminated lumber,* is made from veneers similar to that used in making plywood but with the grain direction in all veneers oriented parallel to one another. The thickness of veneers is between ½ and ½0 in. (3.2 and 2.5 mm) LVL is made by a continuous process, in lengths of 8 to 60 ft (2.4 to 18m), in which grains of all veneers run parallel to the beam length. Veneers are bonded together using PF adhesive.

Because of the high-quality softwood veneers that are used, and as the defects are small and randomized, mechanical properties and reliability of LVL are improved. The allowable value in flexure ranges between 2200 and 4200 psi (15.2 and 29 MPa). The modulus of elasticity varies between 1.8×10^6 and 2.8×10^6 psi (12.4 and 14.3×10^3 MPa).

The cost of this veneer product is relatively higher than that of ordinary lumber. LVL members are used in building construction as headers over openings and main beams. They are also used in the manufacture of I beams (as flanges) and parallel-chord trusses and as scaffold planks.

5.9 CREEP

A wood member subjected to constant load, well below the short-term failure load, may fail if that load is sustained for enough time. *Creep* is the increase in strain or deformation with time under constant stress.

When a member is loaded, it deforms elastically. When the load is maintained continuously, additional deformation takes place, which is the creep or creep deformation. Due to creep deformation, with time, wood beams sag. Creep can take place at very small loads and can continue for many years.

Creep or creep strain becomes a significant factor as the temperature or moisture content increases. At ordinary temperatures creep is aggravated by changes in moisture content. In lumber, creep strain depends on the direction of measurement (longitudinal or transverse direction). Creep strain is much more severe when loaded perpendicular to grain. At low stress levels creep deformation stabilizes after some time. But at higher stress levels the rate of creep increases with time.

When seasoned wood remains dry during service or when unseasoned wood remains wet during service, creep deformation, at low stress levels, can be taken as 50% of elastic deformation. When the load is removed, most of the elastic deflection will be recovered, but the creep component will be permanent. But when green lumber is allowed to dry under service loads, the creep component of deformation is high and can be as much as 3.5 times the elastic component.

Creep can also occur in panel products such as plywood and particleboard. High and cyclic moisture environments accelerate the creep of panel products. An increase in relative humidity from 65% to 80% has resulted in a creep increase (in bending) of 200 to 300%. Creep deflection of hardboard and particleboard specimens at an equilibrium moisture content of 18% is about three to four times that of specimens at 6% moisture content (measured at 40 days).

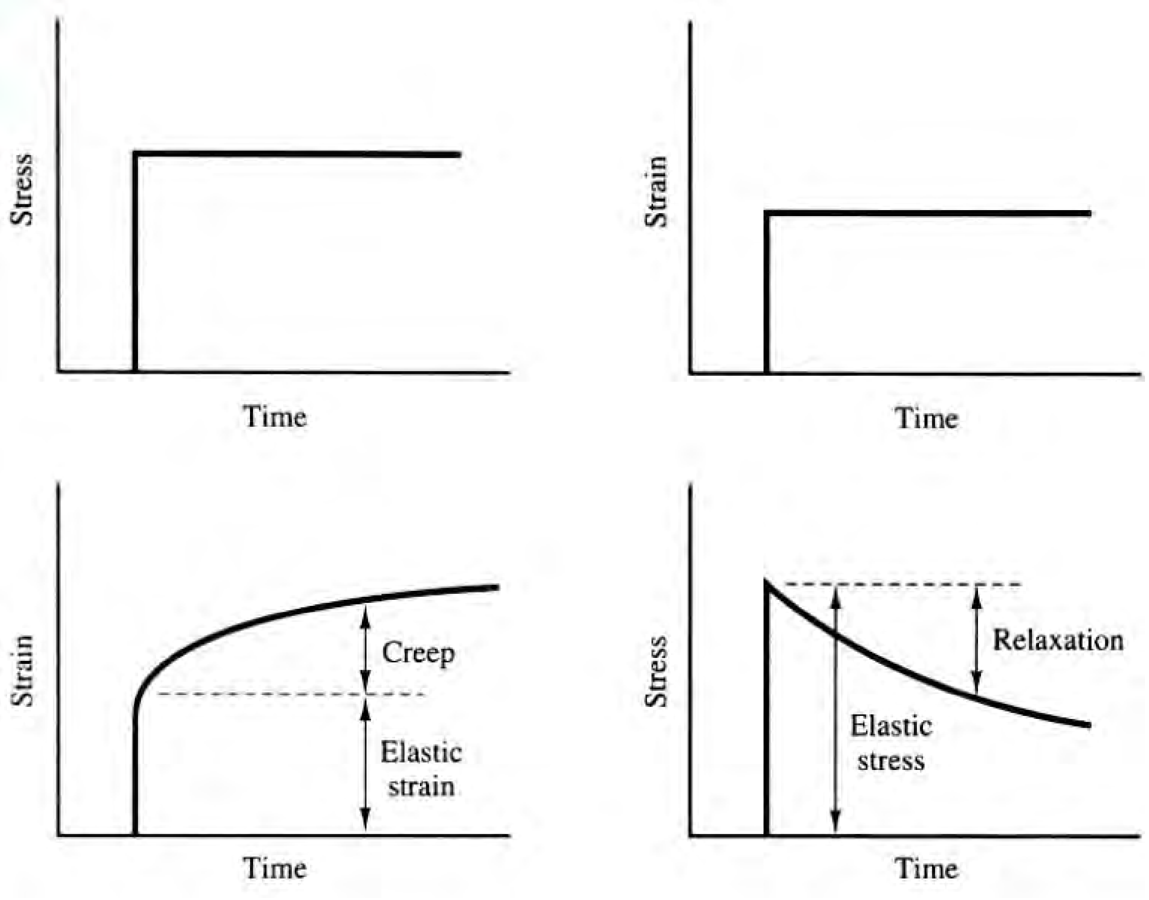


Figure 5.23 Effects of creep.

Creep has two functions: When stress is kept constant with time, creep results in an increase in deformation as shown in Fig. 5.23. But when deformation is controlled (member being clamped), creep results in a stress loss, also called *stress relaxation.*

5.10 WOOD CONSTRUCTION

Wood is the most common construction material for dwellings. It is used in buildings of two to three stories. The advantages of the application of wood are:

- Light weight
- Faster construction
- Reduced foundation load
- Economy
- Material availability
- Simpler connections
- Adaptability to modifications and remodeling
- Need for only simple tools

Building construction using lumber and wood products is called *wood frame construction.* The type of construction shown in the Fig. 5.24 is referred to as *platform*

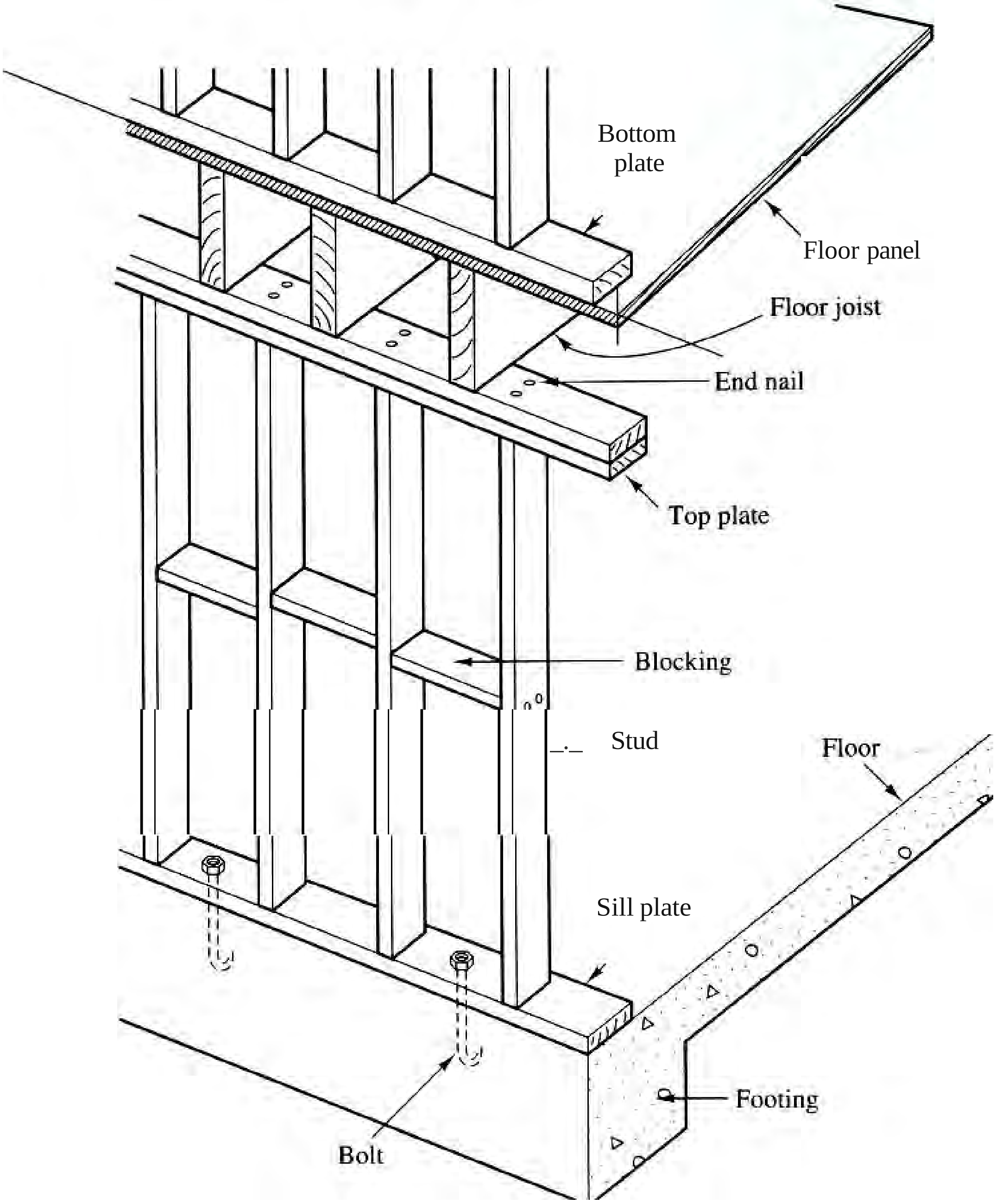


Figure 5.24 Timber construction.

framing construction. In this method of construction, the vertical members do not continue through a floor but stop at the ceiling level in every story.

Typical wood construction consists of a wood frame composed of horizontal (or inclined) and vertical elements that form the structural components of the building. These elements are required to transfer loads from the superstructure to the foundation, which is generally a concrete footing. The vertical components of the frame are called *studs,* and the horizontal or inclined members (roof) are called *rafters* or *joists.*

A stud is one of a series of slender (wood) structural members used as supporting elements in load-bearing walls or partition walls. Nominal 2 x 4 or 2 x 6 members are commonly used as studs. They bear on a continuous horizontal element called a *sill plate* or *bottom plate* which is bolted down to the footing. The sill plate is nominal 2 x 4 or 2 x 6 treated lumber. At the top, the studs are connected by a continuous wood member(s) called a *top plate* or *double plate*. The top plate serves to distribute the floor and roof load to all the studs. In addition, it ties the individual wall elements together. The top plate also works as a firestop. The studs, bottom plate, and top plate make up the load-bearing wall element in a wood frame construction.

The thickness of lumber used as studs depends on the number of stories and the type of wall. For load-bearing walls of one- to two-story buildings, nominal 2 x 4 in. lumber is adequate. For taller buildings and in plumbing walls (when plumbing fixtures are built into the thickness of the wall), nominal 2 x 6 or 2 x 8 may be required. In partition walls, nominal 2 x 4 lumber is adequate. When concentrated loads are acting, posts (size equal to the thickness of the wall) are introduced in the wall.

The spacing of studs is either 16 or 24 in. (0.4 or 0.6 m) on centers, but the latter is more common. The connection to the bottom plate and the top plate is accomplished with end nailing or toe nailing. Intermediate blocking may be required to support the panel nailing and to act as a firestop. Lateral support to the frame is provided by either diagonal bracing or paneling.

The floor loads and roof loads are carried through the floor or roof panel to supporting joists. A *joist* is one of a series of beams, parallel to each other, which support floor and ceiling loads. It rests on the top plate, which distributes the load to the studs. When the joists cannot be supported directly by the top plate, they are connected to the supporting element using joist hangers.

The joists are spaced, generally on 24-in. (0.6 m) centers, and are of Dimension lumber (nominally 2 in. thick). Lateral support to the joists is from the floor panel (plywood or particleboard) and/or by blocking. Electrical ducts and plumbing fixtures are made to run through the depth of the joists by drilling holes through them. Drywall (or gypsum board) nailed to the bottom of the joists hides these fixtures and provides a flat ceiling.

The roof joists (or rafters) are connected to the top plate in a manner similar to the floor joists. A *rafter* is one of a series of structural members of a roof supporting roof loads. The load distribution is *done* by nailing a roof panel to the top of the rafters. The horizontal thrust resulting from the inclination of the roof can be supported by ceiling joists or some other means.

Openings in the walls require modification of the regular stud wall construction. At both ends of an opening double studs are generally provided. To carry the load from the superstructure over the opening, a beam is required, called a *header*. To save on labor costs, sometimes a deeper beam, of depth equal to the height between the top of the opening and the bottom of the top plate, is used. The thickness of the beam is equal to the thickness of the wall. For example, a nominal-4-in.-thick wall may use a header that is nominally 4 in. thick and a nominal-6-in.-thick wall requires a 6-in.-thick header. Connection between individual members is accomplished using galvanized nails. A *stringer* is a cross beam supporting load from floor or ceiling joists. The supporting beam on which the stair treads rest is also called a stringer. A stringer is generally of Dimension lumber of 4 in. nominal thickness.

In addition to the primary elements shown in Fig. 5.24, wooden buildings are provided with many other load-carrying elements. The lumber floor joists can be replaced by manufactured components such as parallel chord truss, I beam, and others. The roof can be built using roof trusses called *trussed rafters*. The beams and headers can be of glulam or laminated veneer lumber.

5.11 TESTING

A number of laboratory tests are described in this section. Following is a list of wood properties and the corresponding test numbers.

PROPERTY	TEST NO.
Moisture content of wood	WOOD-1
Specific gravity of wood	WOOD-2
Compressive strength of wood	WOOD-3
Modulus of rupture of wood	WOOD-4
Modulus of rupture of particleboard	WOOD-5

Test WOOD-1: Moisture Content of Wood

Purpose: To determine the moisture content of green wood.

Related standards: ASTM D143, D4442.

Definition:

- Moisture content is the weight of water in wood expressed as a percentage of its oven-dry weight.

Equipment: Oven, balance.

Sample: Wood in green condition cut to a size of 2 x 2 x 6 in. (50 x 50 x 150 mm).

Procedure:

1. Weigh the sample in green condition: A(g).
2. Accurately measure the dimensions of the specimen.
3. Dry the sample to constant weight in the oven at 103 ± 2° C (for approximately 24 h).
4. Weigh the oven-dry sample: B(g).
5. Calculate the moisture content as

$$\text{moisture content} = \frac{A - B}{B} \times 100$$

Report: Indicate the specimen species and specimen size. Round the calculated moisture content and report.

Test WOOD-2: Specific Gravity of Wood

Purpose: To determine the specific gravity of wood **in** green condition.

Related standards: **ASTM** D2395, D143.

Definition:

- *Specific gravity* is the ratio between the weight of the wood and the weight of an equal volume of water.

Equipment: Graduated cylinder, pointer rod, balance.

Sample: Wood sample of size 2 x 2 x 6 in. (50 x 50 x 150 mm) in green condition.

Procedure:

1. Get the initial weight of the specimen in green condition, W (lb).
2. Measure length, l, width, w, and thickness, t (in).
3. Fill the graduated cylinder (about 12 in. tall) with water about two-third full.
4. Read the water level.
5. Immerse the specimen in the graduated cylinder, and hold it submerged with the slender pointer rod. Read the water level again.
6. The difference in water level is equal to the volume of the specimen, V (in^3). Note: Alternatively, the volume, V, can be obtained using the actual dimensions of the specimen.

$$V = L \times w \times t$$

7. Determine the specific gravity (SG) in green condition as

$$SG = \frac{27.68(W)}{V(1 + 0.01M)}$$

where M is the moisture content in percent and V is the volume in green condition.

8. Specific gravity in oven-dry condition (and volume at test) can be calculated as

$$SG = \frac{27.68(W)}{V(1 + 0.01M)}$$

where V is the volume in oven-dry condition.

Report: Indicate the species. Report the specific gravity values in green and oven-dry conditions.

Test WOOD-3: Measurement of Compressive Strength of Wood Parallel to Grain

Purpose: To determine the parallel-to-grain compressive strength of clear wood specimen.

Related standard: ASTM D143.

Equipment: Universal testing machine, compressometer.

Sample: Clear wood specimen of size 2 x 2 x 8 in. (50 x 50 x 760 mm).

Procedure:

1. The ends of the specimen should be level.
2. Position the specimen under the crosshead of the testing machine, and apply load continuously at 0.024 in/min.
3. Measure the change in length using the compressometer [over a central gage length of 6 in. (150 mm)]. Deformation will be read to 0.0001 in. (0.002 mm).
4. Continue the loading until the proportional limit is well passed.
5. Get the deformation readings to the nearest 0.0001 in. (0.002 mm).

Report: Indicate the species, the moisture content, and the specific gravity. Report the clear wood compressive strength.

Test WOOD-4: Modulus of Rupture of Lumber

Purpose: To determine the bending strength or modulus of rupture of clear wood sample.

Related standard: ASTM Dl43.

Definition:

- *Modulus of rupture* is the extreme fiber stress in bending.

Equipment: Universal testing machine, hard maple bearing block (to apply the load), dial gage.

Sample: Clear wood specimen of size 2 x 2 x 30 in. (50 x 50 x 760 mm).

Procedure:

1. Measure the cross-sectional dimensions accurately.
2. Position the specimen on supports with a span length of 28 in. (710 mm).
3. Apply load at the center of the specimen through the loading block at a rate of 0.1 in./min (2.5 mm/min).
4. Deflection readings should be taken to 0.001 in. (0.02 mm).
5. Measure the load and deflection at intervals.
6. Continue loading until failure.
7. Note the maximum load and type of failure.

8. Plot the load-deflection diagram.
9. Measure the slope of the load-deflection diagram: P/Δ.
10. Calculate the modulus of elasticity, E as

$$E = \frac{(P/\Delta)L^3}{48I}$$

where Lis the span length and/ is the moment of inertia. Note that E has psi units when dimensions are measured in inches and P is in pounds.

11. Draw the moment diagram for the failure load.
12. Calculate the MOR value as

$$\text{MOR} = \frac{3PL}{2bd^2}$$

where P *is* the failure load, bis the beam width, and d the beam depth.

Report: Indicate the species, the specific gravity and the moisture content. Show the size of the specimen. Report MOR and E values.

Test WOOD-5: MOR of Particleboard

Purpose: To determine the bending capacity and modulus of a rupture of particleboard specimen.

Related standard: ASTM D1037.

Equipment: Universal testing machine, bearing block, dial gage.

Sample: ½-in.-thick particleboard of width 3 in. and length 14 in.

Procedure:

1. The specimen is subjected to center loading on a span of 12 in.
2. Support the specimen on bearing blocks 3 in. in width and 1½ in. in thickness.
3. Apply the load continuously through the loading block (Test WOOD-4) at a rate of approximately ¼ in./min.
4. Measure the deflection of the center of the specimen using a dial gage located at the bottom of the specimen.
5. Take deflection readings to the nearest 0.005 in. (0.10 mm).
6. Note the character of failure. Also note whether the failure was in compression or tension.
7. Calculate the MOR value as

$$\text{MOR} = \frac{18P}{bd^2}$$

where P is the failure load, b the width and d the thickness. For $b = 3$ in. and $d = \frac{1}{2}$ in.,

$$\textbf{MOR} = 24(P) \quad \text{psi}$$

8. Plot the load-deflection diagram.

9. Calculate the stress at the proportional limit and the modulus of elasticity.

$$E = 1152(P/\triangle) \quad \text{psi}$$

where $P/$ is the slope of the load-deflection diagram.

Report: Report the values of stress at the proportional limit, modulus of rupture, modulus of elasticity, and type of failure.

CHAPTER 6

Bituminous Materials and Mixtures

Bitumen is a solid, semisolid, or viscous cementitious material, natural or manufactured, and composed principally of various mixtures of complex hydrocarbons. The term *hydrocarbon* refers to any of a class of compounds containing only hydrogen and carbon atoms. Large hydrocarbon molecules such as those in petroleum are formed by the bonding of many hydrogen and carbon atoms. The properties of hydrocarbons depend on the number as well as the arrangement of hydrogen and carbon atoms in the molecule. All bituminous materials are completely soluble in carbon disulfide and are nonvolatile, nontoxic, and soften when heated. The most common bituminous materials are asphalts, tars, and pitches (Fig. 6.1).

Asphalts are cementitious materials in which the predominant constituent materials are bitumens. They are available as natural deposits or are produced from petroleum processing. The consistency of asphalts varies widely from solid to semi-solid at normal temperature. *Tars,* along with pitches, are the products of distillation of materials such as wood, coal and shale. When these materials undergo destructive distillation (means subjecting the raw material to heat alone, without access to air), the resulting condensate is tar. Most tar is a by-product of the distillation or carbonization of coal. Further processing of tar produces a solid or semi-solid residue known as *pitch.* Coal-tar pitch is a bituminous material produced by the partial distillation of coal. Pitches are black or dark brown in color and liquefy gradually when heated.

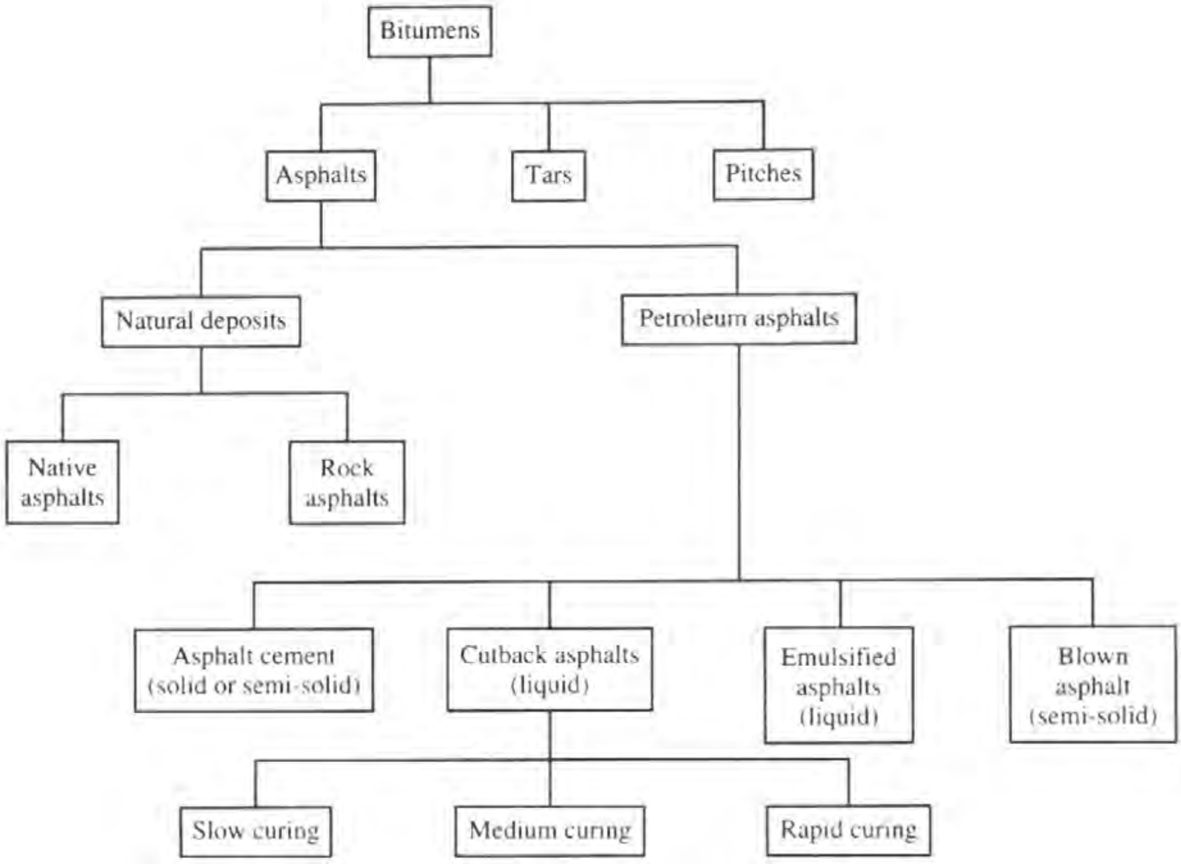


Figure 6.1 Bituminous materials.

Bitumens possess a number of properties that make them useful in the construction industry. Most important are their ability to adhere to solid particles such as aggregate and brick, and their impermeability or water resistance. These properties make a bituminous material idea] for use for pavements, as an impervious layer in built-up roofing, and in the manufacture of roof shingles. Bituminous materials are commonly used in roadways, roofing felt, caulking compound, waterproofing compounds, wallboard, building paper, paints, shingles, and many other construction products. Bituminous compounds are also used widely to provide waterproofing coating for walls and below-grade structures.

6.1 TARS AND PITCHES

When coal is heated in coke ovens, it is reduced to coke. The gases (vaporization of oils) generated during the process are collected from the oven and refined. The distillation of lighter oils produces tar, leaving a hard semisolid residue which is the pitch. As noted earlier, tars and pitches can be produced from organic materials other than coal, but coal tar is the most common.

Tar produced by the destructive distillation of bituminous coal, called bituminous coal tar, is the most commonly used tar in pavement construction. The viscous liquid produced at the end of the distillation process, called *crude tar,* contains a large amount of water as well as some fuel oils. For it to be used in pavement construction, it should be refined. The coal refinery uses a distillation process which is similar to that of bitumen, in which the light and heavy oils are separated. The residual matter or pitch (also called base tar) is fluxed back with tar oils to yield *road tar.*

Tars are highly resistant to natural weathering action and are not as susceptible as bitumen to the dissolving action of petroleum distillates. They tend to oxidize (become brittle) when exposed to heat and air, somewhat more quickly than do the asphalts. Overheating spoils tars more easily. Tars are more susceptible than asphalts to changes in consistency with temperature variation. Tars have been used in the past in pavements and as a waterproofing layer in roof construction, but they have largely been replaced by petroleum asphalts.

Pitches are obtained as residual in the partial evaporation or fractional distillation of tar-primarily coal tar. They gradually liquefy when heated. Tar pitches (and other asphaltic materials) are used for built-up roofing and waterproofing of underground and aboveground construction, such as foundations, retaining walls, dams, and bridges. Aboveground structures experience great fluctuations in environmental conditions, and waterproofing compounds should be able to withstand these changes without becoming brittle or too soft.

6.2 ASPHALTS

Asphalts are the most common and widely used bituminous materials. They are found as natural deposits or are produced from petroleum crude. The term *asphalt* refers to a black cementitious material which varies widely in consistency from solid to semisolid at normal temperatures. With heat, asphalt softens and becomes a liquid. Nearly all the asphalts manufactured in the United States are derived from crude petroleum, when they are called *petroleum asphalts.* The amount of asphalt a crude oil contains varies from source to source. Higher-grade crudes may contain as little as 10% asphalt (the balance is lighter products such as gasoline, kerosene, and fuel oil), whereas lower-grade crudes have as much as 90% asphalt.

The natural deposits of asphalts are of two types:

- Natural rock asphalts
- Native asphalts or lake asphalts

The *natural rock asphalts* or *asphalt rocks* are found in many parts of the world as deposits of sandstone or limestone filled with asphalts through a geologic process. Some soft varieties of limestone contain from 6 to 14% bitumen, and a few crystalline limestones contain 2 to 20% bitumen. These types of rocks are found in some regions of Switzerland, France, and Italy (Sicily). They are also found in California, Texas, and a few other states. Remarkably straight asphalt veins several miles long are found in Asphalt Ridge, Vinta Basin, near Vernal, Utah. Asphalt deposits are also seen in Edna, about 8 miles southeast of San Luis Obispo, California, and in the Sisquoc region of Santa Barbara County, California.

Rock asphalts can be used for surfacing roads when combined with other materials. The use of asphalt rocks is very minimal in the United States due to high costs.

Bitumens also occur naturally as *native asphalts* found in lakes. A number of deposits of asphaltic materials, of wide-ranging properties, are found in Lake Trinidad, West Indies (containing about 40% bitumen mixed with fine siliceous silt, clay, and organic matter); Bermudez, Venezuela (lake asphalt containing about 65% bitumen); Cuba; Texas; Los Angeles (La Brea asphalt pits); and other locations.

In few places in the Middle East (Iran to Pakistan), asphalt seeps from the earth and gets absorbed in sand and dust. These seepages also occur at the bottom of (the Dead Sea) seabed and float on the surface of the water. Natural bituminous soils were collected and used to build walls as far back as the middle of the fourth millennium B.C. (in Babylonia). A combination layer of natural asphalt and clay were used to lay the bricks on regular courses. The bituminous earth was also found suitable for making baked bricks and in pavements. Excavations of settlements dating to about 3000 B.c. in the Indus Valley have revealed the application of asphalt as a waterproof material.

Powdered rock asphalt was used with bitumen in the eighteenth century to build floors and pavements in France. Later, in the nineteenth century, the same technique was used in Switzerland, Germany, and England. A British patent was issued in 1837 for "a mastic cement applicable for paving, road making, covering buildings and other purposes." The first roadway in England was resurfaced with rock asphalt (from France) in 1869. Following the discovery of petroleum asphalt and with the growth of automotive transportation, use of asphalt paving material expanded rapidly. Note that asphalt pavement is built using two materials: asphalt and aggregate. There are many types of asphalt and many varieties of aggregates. Thus it is possible to build different kinds of asphalt pavements-pavements that are suitable for different applications.

6.3 PETROLEUM ASPHALTS

Refining and distillation of petroleum results in various types of asphalt or asphaltic material. Distillation is a process in which various fractions (products) are separated out of the crude by raising its temperature in stages. Gasoline is distilled at a temperature of 100 to 400°F (37 to 204°C), whereas asphalts are distilled at temperature above 900°F (482°C).

The petroleum refining process is divided into two groups:

- Fractional distillation
- Destructive distillation (cracking)

The *fractional distillation* process involves the separation of crude oil into various materials without significant changes in the chemical composition of each material. The various materials are removed at successively higher temperatures (using steam or vacuum) until the petroleum asphalt is obtained as the residue. Further processing of the residue yields asphalts of different grades and types.

The *destructive distillation* process involves the application of intense heat [temperature as high as l 100°F (593°C)] and high pressure [as high as 7-35 psi or (5 **MPa)],** which will cause chemical changes in the material. This method is used when larger amounts of lighter fractions of the materials (such as motor fuels) are required. Asphaltic material obtained from the destructive distillation process is not widely used in pavement construction, as it is more susceptible to weather changes than is asphalt produced from fractional distil1ation. Most asphalt used in pavements, is steam-refined asphalt.

Petroleum asphalts are classified into four types (Fig. 6.2):

- Asphalt cements
- Cutback asphalts
- Emulsified asphalts
- Air-blown asphalts

Cutback asphalts are further divided into three types:

- Slow-curing cutback asphalts
- Medium-curing cutback asphalts
- Rapid-curing cutback asphalts

Petroleum asphalts are used extensively in the construction of flexible pavements. They are also used in roof construction (rolled roofing, asphalt shingles, and built-up roofing), for insulation (electrical insulation and as building paper), and for waterproofing (sprays, paints, and use of bituminous fabrics). Petroleum asphalts are also employed in the lining of canals and to seal subgrades for preventing the migration of water. Joint seals generally use petroleum asphalts (with or without mineral fillers).

6.3.1 Asphalt Cement

Asphalt cement (also called *paving asphalt)* is a type of asphalt that is very sticky and highly viscous. it can also be described as asphalt especially prepared with the quality and consistency required in the manufacture of asphalt pavements (hot-mix pavements). It is obtained after separation of the lubricating oils from the crude oil.

Asphalt cement possesses excellent binding properties and adheres very well to aggregate particles. In addition, it has excellent waterproof qualities. Pavement built using paving asphalt is waterproof and is resistant to many types of chemical attack.

Asphalt cement is a highly viscous material; consequently, when used in pavement construction it is necessary to heat both the asphalt cement and the aggregates prior to mixing. Asphalt cements have penetration readings ranging between 5 and 300. For use in pavement construction the asphalt cement must have a minimum penetration reading of 40 and a maximum of 300 (at a load of 100 g in 5 seconds at 77°F).

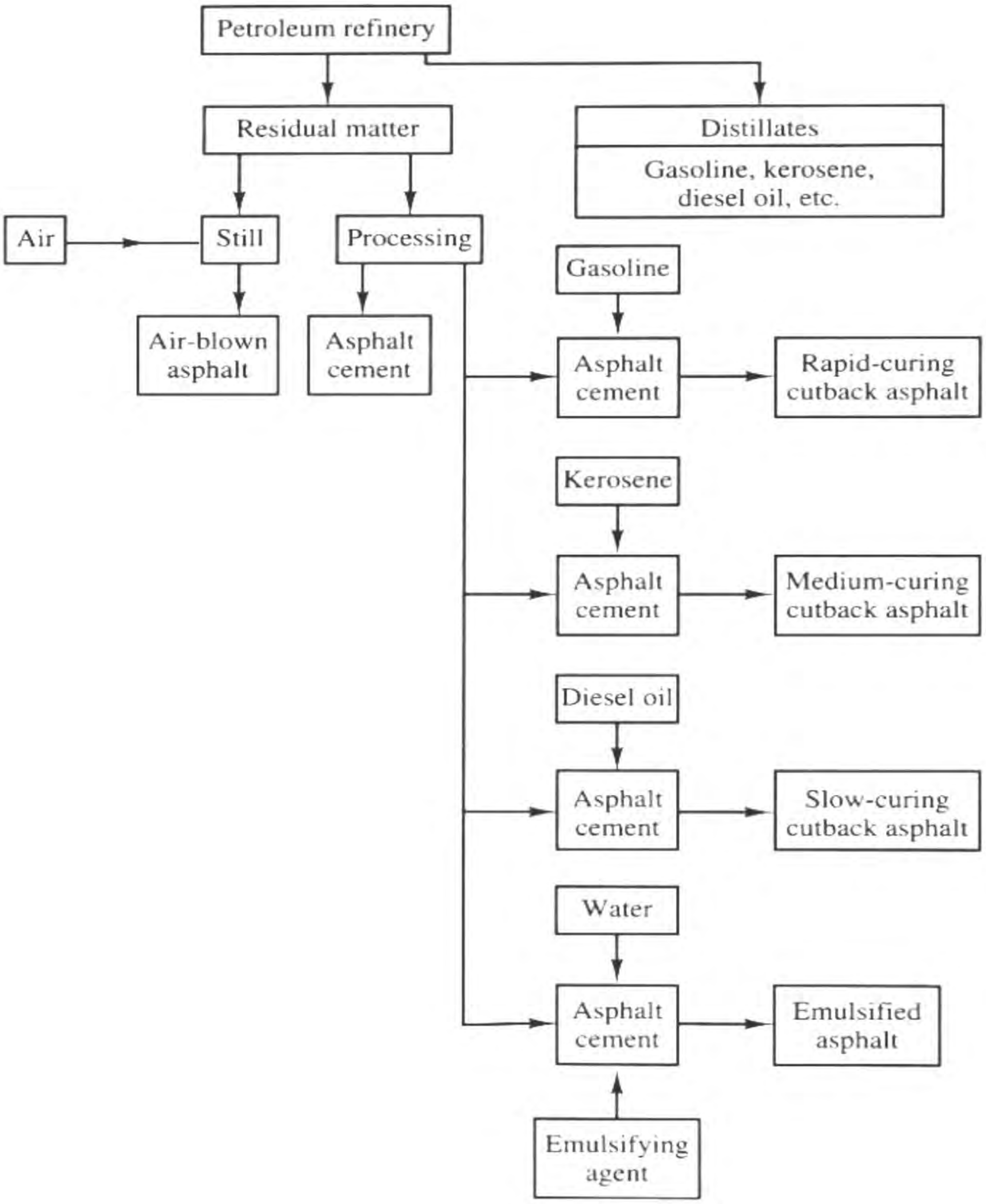


Figure 6.2 Petroleum asphalts.

6.3.2 Cutback Asphalts

Cutback asphalt is asphalt cement that is liquefied by blending with petroleum solvents (called *diluents).* The diluents evaporate upon exposure to the atmosphere, leaving asphalt cement behind. With cutback asphalts it is possible to use asphalt in pavement construction without the application of heat.

Cutback asphalts are constituted from a base asphalt of selected hardness or viscosity dissolved in a solvent of high, medium, or low volatility. The resulting asphalts have distinctive properties that make them useful in different applications. As noted earlier, when the solvent evaporates, asphalts of different hardness or viscosity are left behind on the aggregates. The curing rate and the characteristics of the residual asphalt depend on the type of cutback asphalt: rapid-curing, medium-curing, or slow-curing.

The terms *rapid-curing, medium-curing,* and *slow-curing* refer to the volatility of the diluents. *Rapid-curing cutback asphalt* is asphalt cement blended with naphtha or gasoline-type diluents of high volatility. The diluents in rapid-curing asphalt evaporate quickly. It is used primarily in mixed-in-place pavement mixes and surface treatments. *Medium-curing cutback asphalt* is cutback asphalt obtained by blending asphalt cement with kerosene-type diluent of medium volatility. It hardens faster than the slow-curing type and slower than the rapid-curing type. This type of asphalt is used for cold-laid pavement bases (plant mixed and mixed in place) and surface treatments. *Slow-curing cutback asphalt* is asphalt cement blended with oils of low volatility, such as diesel oil. Its viscosity value is low and it hardens very slowly. It is used for cold-laid pavement bases.

The curing rate and characteristics of the residual asphalt (after the evaporation of the solvent) depend on the type of cutback asphalt. These two factors should be considered in selecting one type of cutback asphalt over the others. The type of aggregate used may also influence the selection. For example, an aggregate deficient in finer particles may require harder asphalt, while a softer asphalt may be used with dense-graded aggregate. Note that when the voids between compacted aggregate particles are relatively small, the gradation is termed *dense graded.*

In addition to the uses described above, cutback asphalts are used in highway construction for priming the road surface prior to surface treatment, seal coating, and in the base course for cold application. Note that cutback asphalts and emulsified asphalt are two categories of asphalt that are available in liquid form.

One of the disadvantages of the use of cutback asphalts is that the volatile distillate may evaporate in the air and add to air pollution. The amount of emission depends on the type, grade, and amount of cutback asphalt, the type of construction, and the atmospheric conditions. The rapid-curing type produces the largest amount of air pollution, and the slow-curing type produces the lowest. Another disadvantage is that the distillate in the cutback asphalt poses fire and toxicity hazards.

6.3.3 Emulsified Asphalt and Blown Asphalt

Emulsified asphalt is an emulsion of asphalt cement and water containing a small amount of an emulsifying agent. Soaps, water-soluble chemicals, and fine clay are used as emulsifying agents. The water forms the continuous phase of the emulsion, and minute globules of asphalt form the discontinuous phase. The water content is generally on the order of 12 to 15%. Asphalt particles remain in suspension as long as water does not evaporate or emulsifier does not break down.

Emulsions have been available since 1903, and used extensively since the 1920s. Prior to this, most flexible pavements had been primarily hot plant mixtures using asphalt cement. Some emulsions that are presently available have better adhesion on aggregates that are high in silica and quartz, whereas others have better bond on limestone aggregates.

A total of 12 grades of emulsified asphalt are covered in ASTM D977. These can be used for spray application, slurry seal, and as subbase, base, and surface course for pavements. The advantage of the use of emulsified asphalt is that it can be applied during damp weather and with aggregates that are cold or hot. In addition, the quantity of materials applied is controlled automatically because any excess (water) will drain into the subgrade. The use of emulsified asphalt also eliminates the use of fuel required to heat and dry the aggregates in the asphalt cement mixtures and reduces energy requirements through reduction or elimination of petroleum distillates that are used in cutback asphalts.

One of the disadvantages of using emulsified asphalt is that because the asphalt is suspended in water, it is susceptible to being washed off a road surface by rain if not sufficiently cured. The unbroken emulsions may be carried into streams, causing ground contamination.

Blown asphalt is obtained by blowing air through the semisolid residue obtained during the later stages of the distillation process. This type of asphalt is relatively firm in consistency compared to other asphalts and is the stiffest asphalt made. Blown asphalts are reasonably ductile. They are highly weather resistant and can withstand temperature changes very well. But extensive blowing reduces the ductility, and hence fully blown asphalts are not used in pavement construction. Blown asphalts possess unique properties that make them suitable for use in roofing materials, waterproof paints, joint fillers (for concrete pavements), and for undersealing old, rigid pavements. They are also used to make mineral rubber, a rubberlike material derived from petroleum.

6.4 PROPERTIES OF ASPHALT

Properties of asphalt or asphaltic material that are of great importance in pavement design and construction are:

- Adhesion
- Consistency
- Specific gravity
- Durability
- Rate of curing
- Ductility
- Aging and hardening
- Resistance to reaction of water

Some of these properties are explained in the following sections.

6.4.1 Consistency

Consistency is a property that measures the degree of fluidity or plasticity of asphalt cement at any particular temperature. The consistency of an asphaltic material may vary from solid to liquid, depending on the temperature of the material. Moreover, it should be noted that asphalts can exist in liquid, semisolid, or solid form. Because of this there is no single technique or instrument that will effectively measure the consistency of all types of asphalts. At any particular temperature, the consistency indicates the grade of the material.

Asphaltic materials having the same consistency at a standard temperature may show different consistency readings at elevated temperatures. The effect of temperature on the consistency is not the same for all asphaltic materials. Consistency of blown asphalt is less affected by temperature than that of asphalt cement.

Viscosity. At temperatures between 160 and 300°F (70 and 150°C), asphalt behaves as a viscous liquid. Below 160°F (70°C), the behavior can be described as linearly viscoelastic. Below about --4°F (-20°C), asphalt becomes a weak and brittle elastic solid.

In a liquid state, the consistency of asphalt is determined by measuring the viscosity of the material. *Viscosity* is a measure of the resistance to flow and is the fundamental consistency measurement in absolute units. It is the ratio of shear stress and shear rate. At temperatures above 300°F (150°C), the ratio of shear stress to shear rate is constant for asphalt cement. When the temperature decreases, as noted earlier, the asphalt cement behaves like a viscoelastic semisolid material, and the ratio of shear stress to shear rate is not constant.

Deformation under load of liquids and semisolids is dependent on the load as well as the duration of load. The longer the duration, the greater the deformation. Differences in deformation between liquids is due to the difference in their viscosities. For materials with high viscosity, deformation is low. For example, diesel oil is nearly 10 times as viscous as water and has lower deformation. Asphalts are more than 10,000 times as viscous as diesel oil. Cutback asphalts, due to the solvents in them, have lower viscosity than that of the original asphalt. Since the range of viscosities of bituminous materials is large, no one instrument or method can be suitable for all. Viscosity of asphalt cements is measured using a viscometer.

Absolute viscosity is a method of measuring viscosity using poise as the basic measuring unit. The method makes use of partial vacuum to induce flow in the viscometer. *Kinematic viscosity* represents a method of measuring viscosity using *stoke* as the basic measuring unit. It is a measure of the flow behavior or resistance to flow under gravity.

Kinematic viscosity is defined as the ratio between the viscosity and the density of the liquid. The unit is mm^2/s or m^2/s. Stoke is kinematic viscosity in 1 cm^2/s. The centistoke (cSt) which is 1 mm^2/s, is customarily used.

Poise is a centimeter-gram-second (cgs) unit of absolute viscosity, equal to the viscosity of a fluid in which a stress of I dyne per square centimeter is required to maintain a difference in velocity of I centimeter per second between two parallel planes in the fluid that lie in the direction of flow and are separated by a distance of I centimeter.

Absolute viscosity, which is also called *coefficient of viscosity,* is often used to measure the resistance to flow of a liquid. It measures the ratio between the applied shear stress and the rate of shear. The cgs unit of absolute viscosity is l g/(cm-s), which is the poise (P). The SI unit of viscosity is l Pa-s which is equivalent to IO P. Stoke is a unit of kinematic viscosity equal to the viscosity of a fluid in poise divided by the density of the fluid in grams per cubic centimeter. The density is mass per unit volume of a liquid and the cgs unit of density is 1 g/cm^3.

As noted earlier, viscosity is measured using viscometers (ASTM D2170). A number of viscometers (reverse-flow), such as the Cannon-Fenske viscometer, Zeitfuchs cross-arm viscometer, and Lantz-Zeitfuchs viscometer, are available for use. In all of them the liquid flows into a timing bulb not previously wetted by the sample, allowing the measurement of the time. The kinematic viscosity is then calculated by multiplying the time (for outward flow) in seconds by the viscometer calibration factor.

The coefficient of viscosity or absolute viscosity of asphalts is measured using vacuum capillary viscometers **(ASTM** D2171). A number of capillary tube viscometers, such as the Cannon-Manning vacuum capillary viscometer, Asphalt Institute vacuum capillary viscometer, and modified Kopper vacuum capillary viscometer, are available for use.

A capillary tube viscometer consists of a calibrated glass tube that measures the flow of asphalt. It is mounted in a temperature-controlled water bath that is preheated to 140°F (60°C). A sample of asphalt cement heated to the same temperature is poured into it. The preheated asphalt cement is too viscous to flow readily through the narrow opening in the tube, and to aid the flow, a partial vacuum is applied to the small end of the tube. The liquid asphalt, with the aid of vacuum, is drawn through the tube. The flow rate is determined by carefully timing the flow from one mark to the other. The measured time is converted to poise by multiplying the flow time by the viscometer calibration factor.

Penetration. Viscosity or consistency of solid and semisolid bituminous materials can also be measured empirically by the *penetration test* (ASTM D5). For many years the only method that was commonly used to record consistency of asphaltic materials was the penetration test (invented by **H.** C. Bowen in 1889).

Penetration is the consistency of a bituminous material expressed as the distance in tenths of a millimeter that a standard needle penetrates a sample of material vertically under known conditions of loading, time, and temperature (Fig. 6.3). A higher value of penetration indicates a softer consistency. The load is the total moving weight of the needle and the attachments (100 g and 200 g as required for the condition of the test). The needle is left to penetrate the sample for 5 seconds. The penetration is given as the distance of units of 0.1 mm that the needle penetrates. For example, if the needle penetrates a distance of 2.2 cm, the penetration is 220.

The penetration test provides an indirect measurement of consistency, and the more fundamental tests described earlier are better measures of the consistency. Note that asphalt cements have an upper limit on penetration of 300 (under a load of 100 g for 5 seconds at 77°F). An asphaltic material that has a penetration reading above 300 should be considered a liquid asphalt (such as cutback asphalt), and a penetration test cannot be used to determine the viscosity of that material. Asphalts having penetration readings below 10 are called solid asphalt.

The addition of natural rubber in very small quantities (less than 5%) to asphalts increases the viscosity and decreases the penetration. In addition, rubber renders the asphalt less susceptible to the action of temperature fluctuations. Due to these changes in properties, the asphalt pavement (with added rubber) becomes more elastic and durable.

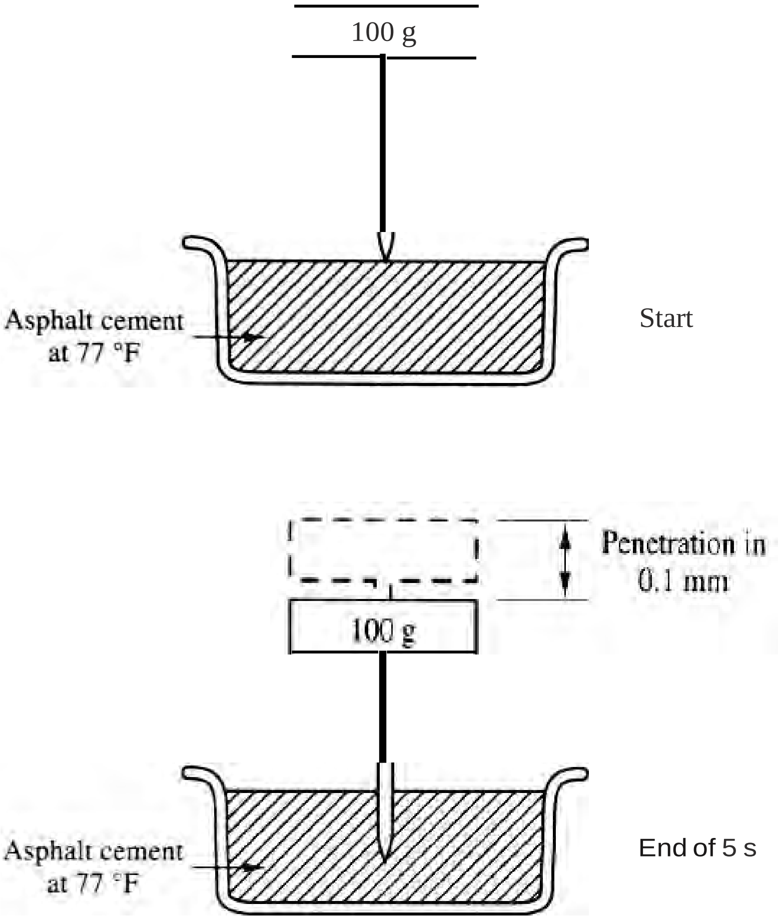


Figure 6.3 Penetration test.

6.4.2 Specific Gravity

Specific gravity and density of semisolid bituminous materials can be determined using the procedure described in ASTM D70. Specific gravity is normally measured using a pycnometer. Since the volume of a bituminous material changes with temperature (from semisolid to liquid state), the specific gravity should be expressed at a given temperature.

The *specific gravity* of asphalt is defined as the ratio of the mass of the given volume of the material at 77°F (25°C) or at 60°F (15.6°C) to that of an equal volume of water at the same temperature. Petroleum asphalts have specific gravity values close to unity (0.95 to 1.05). The specific gravity of road tars generally varies between 1.08 and 1.24. Specific gravity decreases with increasing temperature. For example, asphalt cement has a specific gravity of 1.0 at a temperature of 60°F (l 5°C), 0.9187 at 300°F (149°C), and 1.0176 at l0°F (-12°C).

A knowledge of specific gravity is essential to determine the percentage of voids in the compacted material. Its measurement is required to convert volume measurement of asphalt to units of mass.

6.4.3 Durability

Durability can be defined as the property that permits a pavement material to withstand the detrimental effects of moisture, air, and temperature. The performance and durability of an asphaltic pavement is affected by a number of factors, including mix design, properties of aggregates, and workmanship, as well as the properties of asphalt. With so many factors controlling the durability, its measurement is rather difficult. Nonetheless, there are laboratory tests to determine the durability of asphalt: thin-film oven test (ASTM D1754) and rolling thin-film oven test (ASTM D2872) to determine the effects of heat and air on asphaltic materials. These tests offer a measure of changes that take place in asphalt over. Time.

Oxidation is the chemical reaction that takes place when asphalt is exposed to oxygen in air. When asphalt oxidizes, the hydrogen in the asphalt combines with oxygen in the air and is removed as water molecules. The loss of hydrogen increases the carbon/hydrogen ratio, leading to hardness in the material and loss of ductility and adhesion. This reaction occurs most readily at higher temperatures and in thin asphalt films. The oxidation causes gradual hardening and loss of plasticity. Note that all asphalts do not harden at the same rate. Oxidation in pavements can be minimized by keeping the amount of air voids low and coating the particles thick.

Volatilization is the process by which lighter hydrocarbon from the asphalts get evaporated. As in oxidation, this process results in the loss of plasticity in asphalt. Volatilization is also affected by the temperature. The higher the temperature, the higher is the rate of volatilization. The rate of oxidation and volatilization nearly doubles for each l8°F (I0°C) rise in temperature.

When a sample of asphalt is heated and then allowed to cool, its molecules will be rearranged to form a gel-like structure, causing it to harden with time. The rate of hardening decreases with time and is insignificant beyond l year. This process happens even when oxidation and volatilization are prevented from occurring. This process of natural hardening of asphalt is called *age hardening.*

6.4.4 Rate of Curing

The process of evaporation of solvents from cutback asphalts and the attendant thickening of the material is called *curing.* It can also be described as the change in consistency of an asphaltic material due to the progressive loss of diluents by evaporation. The *rate of curing,* or the time required for a cutback asphalt to harden and develop consistency that is satisfactory for the function as a binder in the pavement (from its original liquid consistency), is an important property of cutback asphalts.

The rate of curing is influenced by the volatility or evaporation rate of the solvent, the amount of solvent, and penetration (or viscosity) of the asphalt base. In addition, the curing rate is affected by the temperature of the environment, surface area of the pavement, and wind velocity. The less solvent, the faster is the rate of evaporation. The curing time increases with the penetration (or increase in softness) of the base asphalt.

In emulsified asphalts the rate of evaporation of water depends on the weather conditions, such as humidity and temperature. With favorable weather conditions, the water evaporates quickly and curing progresses rapidly.

6A.5 Resistance to Action of Water

Asphaltic materials used in pavements should be able to withstand the effects of water. The durability of the pavement is greatly affected by the ability of asphalt to adhere to aggregate particles in the presence of water. Loss of bond in the presence of water may lead to deterioration of the pavement. Generally, pavements built using paving asphalts are waterproof and resistant to many types of chemical action. Complete drying of the particles prior to mixing will improve pavement performance.

6.4.6 Ductility and Adhesion

Ductility is an important properly of asphaltic materials. Brittle materials do not perform well in pavement construction. But the exact value of ductility (if it can be measured) is not as important as the existence of ductility characteristics. The ductility of asphalt can be tested using the procedure described in ASTM D113.

Ductility is measured as the distance to which an asphalt sample will elongate before breaking when two ends of a briquette specimen are pulled apart at a specified speed and temperature. The test is commonly conducted at a temperature of 77°F (25°C) and a speed of 5 cm/min. The ductility thus measured provides a measure of the tensile properties of the material. Experience has shown that asphalts with low ductility show the most pitting and cracking or disintegration.

Ductility is sometimes used as an indirect gage of adhesion and cohesion of the asphaltic material. *Adhesion* is the ability to stick to the aggregate particles in the pavement. *Cohesion* is the ability to hold the particles firmly in place. Adhesion refers to the molecular force that exists in the area of contact between unlike bodies (e.g., adhesive tape), whereas cohesion refers to the molecular force that acts to unite the particles (e.g., cohesive organization). Ductile material with sufficient bonding characteristics, such as asphalt and tar, exhibit excellent adhesive and cohesive properties.

But the requirements for these properties vary from one application to another. For example, compounds that are used as damp proofing or waterproofing materials in above- ground structures should possess greater ductility and higher tensile strength than those in underground structures exposed to moderate temperature fluctuations.

To guarantee good adhesion of asphalt in pavement construction it is necessary that the aggregate particles be clean, dry, and free from dust. The presence of moisture may make it difficult for the asphaltic binder to displace moisture from the surface and adhere to the particles.

6.5 ASPHALT GRADES

Asphalt cements are graded based on the viscosity values at l40°F (60°C) and 275°F (135°C). This grading system, called the *viscosity grading system*, is done by prescribing limiting values of consistency at these two temperatures. The lower temperature represents the maximum temperature the pavement is likely to experience during service, and the higher temperature approximates the mixing and laydown temperature.

The five viscosity grades of asphalt cement are AC-2.5, AC-5, AC-10, AC-20, and AC-40 (ASTM D3381). AC-2.5 grade has a viscosity of 250 P (at 140°F), and AC-40 has a viscosity of 4000 P. The higher the value in poise, the more viscous is the asphalt.

Asphalt cements of grades AC-5 and AC-10 are used in asphalt concrete pavements in regions where the mean annual temperature is less than 45°F (7°C). When the mean annual temperature exceeds 75°F (24°C), asphalt cements of grade AC-20 or AC-40 is recommended. In regions of mean annual temperature between 45°F (7°C) and 75°F (24°C), grade AC-10 or AC-20 is recommended.

Asphalt cements can also be graded based on the penetration measurement. The penetration grades of asphalt cement are grade 40-50, grade 60-70, grade 85-100, grade 120-150, and grade 200-300 (ASTM D946). Note that viscosity grades for asphalt cements have, in addition, minimum penetration requirements. For example, grade AC-40 has a minimum penetration requirement of 20, and AC-2.5 has a minimum penetration requirement of 200.

Cutback asphalts are graded based on their kinematic viscosity at 140°F (60°C) in centistoke (ASTM D2026, D2027, and D2028). All three types of cutback asphalt (slow curing, medium curing, and rapid curing) have four grades: grade 70, grade 250, grade 800, and grade 3000, depending on the kinematic viscosity values. Grade 70 has a minimum kinematic viscosity value (at 140°F) of 70 cSt and a maximum of 140 cSt. Grade 250 has minimum and maximum values of 250 and 500 cSt, respectively. Grade 800 has minimum and maximum values of 800 and 1600 cSt, whereas grade 3000 has 3000 and 6000 cSt, respectively.

In addition to these four grades, the medium-curing type has an additional grade, grade 30, which has the minimum and maximum kinematic viscosities of 30 and 60 cSt. The difference in these grades is attributed to the amount of diluents; the smaller the amount of diluent, the higher is the grade. The choice of a particular grade or type of cutback asphalt depends on several factors, including the environmental conditions relative to the application. A pavement that is generally under a hot sun most of the time during service may require rapid-curing asphalt to provide a harder asphalt base and stable pavement. On the other hand, to obtain similar pavement characteristics in a cold region, slow-curing or medium-curing asphalt may be preferred.

6.6 ASPHALT CONCRETE

The term *concrete* generally means a solid mass made by cementing together aggregate particles. Portland cement concrete is made by mixing together portland cement and water with coarse and fine aggregates. *Asphalt concrete* is made by mixing hot asphalt cement with heated aggregates and compacting the mix to form a uniform dense mass. Emulsified asphalt can be used instead of asphalt cement.

Asphalt concrete is used for the construction of asphalt pavement, which is also called *flexible pavement,* due to its ability to conform to settlement of the foundation. Asphalt concrete pavements are used for highways, airports, parking lots, and driveways.

In asphalt concrete, the framework of aggregates is held in place by the binding action of the asphalt cement (Fig. 6.4). The function of asphalt cement is to hold the particles in place. Selected aggregates are compacted so that the external loads are distributed by point-to-point contact of the aggregate particles. This mechanism of load transfer is called *aggregate interlock* (or *intergranular pressure* or *internal friction).*

The voids or spaces between particles are partially filled with asphalt cement, leaving sufficient air pockets, which account for roughly 2 to 6% of the concrete volume. The amount of asphalt cement should be such that the concrete has more than 2% air voids. Too much cement (or too few air voids) allows the particles to float, which displaces the particles. Too little cement or binder causes inadequate bonding, and potholes are produced.

6.6.1 Aggregates

In asphalt concrete pavement, aggregates may comprise about 70 to 75% by volume or 90 to 95% by weight. The external loads are distributed through point to point contact or aggregate interlock. Aggregates also provide resistance to abrasion under traffic and skid resistance. The functions of asphalt are to bind the particles and act as a waterproofing ingredient. Excessive amounts of the binder tend to lubricate the particles and lower the stability of the pavement. Asphalt also allows the particles to rebound upon removal of the load, but the major share of the resistance to deformation is from the aggregate framework.

A number of factors, such as quality, gradation, shape, stiffness, and quantity of aggregates, determine the effectiveness of this load transfer and the stability of pavement. *Stability* is the resistance to deformation under load. It is this property that enables a pavement to withstand the traffic without sustaining permanent deformation.

Internal friction or aggregate interlock represents the resistance to movement of particles past one another under the action of applied load. The resistance is caused by

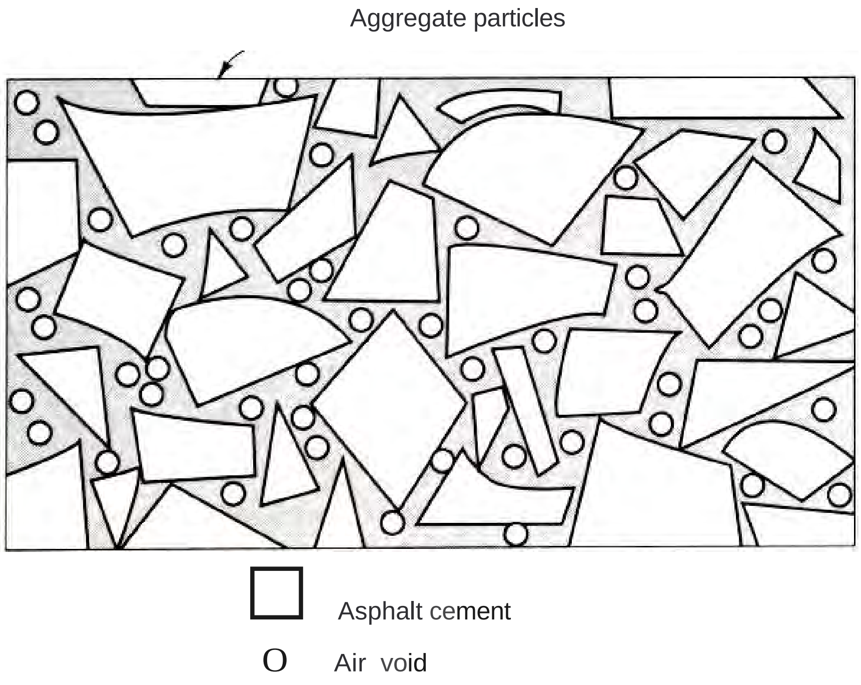


Figure 6.4 Aggregate interlock mechanism.

the interlocking of particles and the surface friction. Crushed stone aggregate has very good internal friction. Gravel is relatively low in internal friction because of the round shape and the smooth surface of particles. Blast furnace slag, which is a by-product in the manufacture of iron (consisting primarily of silicates and aluminosilicates of lime), has very high internal friction.

It was indicated earlier that an average of about 95% of asphalt concrete by weight or 75% by volume is made up of aggregate particles. The asphalt binder is about 5% by weight. As the aggregates occupy a very large portion of asphalt concrete, the performance of pavement is influenced by the aggregate properties. Rounded particles (gravel and sand) are less stable, and due to the tendency to slide over each other are less effective in load transfer. Angular particles (crushed stone or rock) are more stable, owing to their shape and texture.

Soft aggregate particles can break and wear under load. The aggregate mass should be as impermeable as possible to keep water out of the mix and the subgrade. Dense-graded aggregates can be compacted to fill the maximum volume in the mass, producing the maximum surface contact and the least void space.

The particles should remain on the surface all the time to yield a skid-resistant surface. The surface texture of the pavement should be coarse to grip the tires when the surface is wet. When the asphalt is too soft or there is too much asphalt in the pavement, the aggregate particles are forced down the pavement. As a consequence, the surface becomes smooth and slick, resulting in a weak top layer.

The amount of asphalt cement should be such that the cement binds or holds all the particles but is not enough to lubricate them so as to cause slippage. Too much asphalt content in the mix results in downward movement of aggregate particles or upward movement of the binder. This movement of asphalt cement to the top surface is called *bleeding* or *flushing.* Placement of aggregate chips on a coating of asphalt cement (seal coat) will control bleeding. (Note that bleeding in concrete is the upward movement of softer particles: cement, water, and fine sand).

Asphalt concrete is made using fine aggregate or a mixture of fine and coarse aggregate with or without a mineral filler. The *mineral filler* is a finely divided mineral product at least 70% of which will pass a 75-μm (No. 200) sieve. Pulverized limestone is the filler most commonly used. Other fillers include stone dust (rock dust), hydrated lime, portland cement, and fly ash.

Grading. The *coarse aggregate* is a graded aggregate made up of particles that are retained on a No. 4 sieve. *Fine aggregate* is a graded aggregate and consists of particles that almost entirely pass a No. 4 sieve. The standard requirements for these two aggregates are given in ASTM D692 and D1073. The coarse and fine aggregates used for asphalt concrete can be crushed stone, crushed slag, crushed gravel, and natural or manufactured sand prepared from stone, crushed blast furnace slag, gravel, or a combination thereof.

Well-graded aggregate is an aggregate that is uniformly graded from the maximum size down to the filler, with the object of obtaining an asphalt mix that has a controlled void content or high stability. *Macadam* is a coarse aggregate of uniform size usually of stone, slag, or gravel.

Three types of gradation are commonly used in pavement construction:

- Open graded
- Intermediate graded
- Dense graded

Open-graded aggregate is an aggregate containing little or no fine aggregate, or one in which the void space in the compacted aggregate is relatively large (Fig. 6.5). It contains less than 10% passing a No. 10 (2-mm) sieve and less than 2% passing a No. 200 (75-μm) sieve. The nominal maximum size is generally equal to or less than 2½ in. (63.5 mm).

Open-graded aggregate is used to make open-graded asphalt concrete, which provides good skid resistance and high permeability so as to permit good surface drainage.

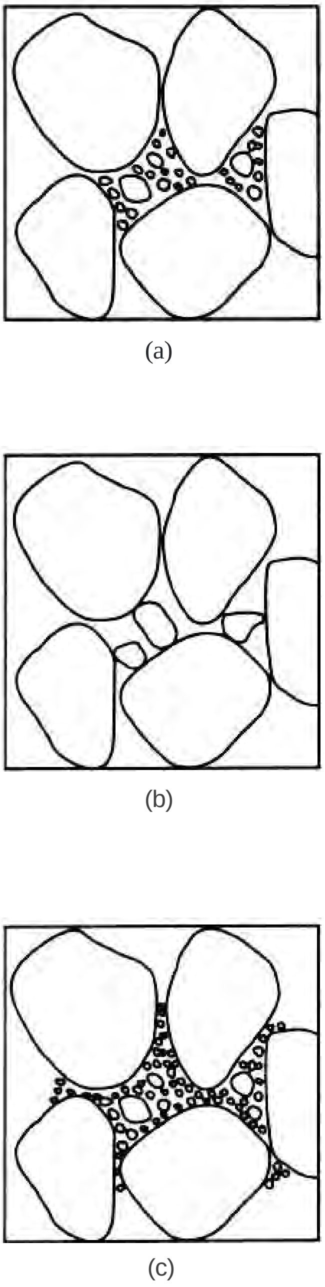


Figure 6.5 Types of gradation: (a) dense-graded; (b) open-graded; (c) too much fines.

A high void content (as much as 20%) allows the moisture to be removed very quickly and gives a rough surface texture. This quick removal of moisture from the surface minimizes the danger of hydroplaning and improves skid resistance during wet season.

Intermediate-graded mix contains a larger percentage of sand (compared to open-graded), usually 8 to 18% passing a No. 8 sieve (2.36 mm). It is well graded from coarse to fine, and may consist of crushed stone or gravel. Both open-graded and intermediate-graded base layer require a surface course (or seal coat) to make the surface impermeable.

Dense-graded aggregate may be composed of crushed stone, slag, crushed gravel, or a mixture thereof. It is well graded, containing coarse-to-fine material, but the amount of fines passing a No. 200 sieve (75 m) should not exceed 5%. Increase in the fine fraction increases the asphalt requirement and slows the curing rate. Use of dense-graded aggregate provides a dense and impermeable layer and does not normally require surface treatment or a seal coat.

The composition of bituminous mixture should follow the recommendations in ASTM D3515. The fine and coarse aggregates are proportioned so that the combined mix falls within the specified grading requirements. Although the nominal maximum size of aggregate can be as high as 2½ in. (63.5 mm), it is generally ¾ in. (19 mm) for most pavements. More than 90% of aggregate particles are retained on a No. 200 sieve.

As discussed earlier, rock dust (mineral filler), which is a by-product of mining operations is used to reduce the amount of voids. The finer particles also assist in smooth placement of the mix and prevent segregation.

6.6.2 Types of Asphalt Concrete

Hot-mixed asphalt **(HMA)** consists of a mixture of hot asphalt and aggregates produced at a batch or drum mixing facility that must be spread and compacted while hot. Both aggregates and asphalt cement are heated prior to mixing to drive off moisture from the aggregate particles and make asphalt cement sufficiently fluid. After heating, all the raw materials are mixed in the plant. The hot mixture is then transported to the paving site and spread in a loosely compacted layer to a uniform, even surface with the help of a paving machine. While the mixture is hot it is compacted by heavy, motor-driven rollers to produce a smooth, well-compacted paving course.

The different types of asphaltic concretes are:

- Hot-mixed, hot-laid bituminous mixtures
- Cold-mixed, cold-laid bituminous mixtures

A *hot-mixed, hot-laid bituminous mixture* is fine aggregate or a mixture of coarse and fine aggregate, with or without mineral filler uniformly mixed with asphalt cement, tar, or emulsified asphalt. The aggregates and the bitumen are heated prior to mixing. The asphalt cement is heated to a temperature not exceeding 350°F (I 76.6°C) and the emulsified asphalt to a temperature not exceeding 180°F (82.2°C). The viscosity grade or penetration grade of the bitumen depends on the type of construction, climatic conditions, and the amount and nature of traffic. As the aggregates are thoroughly dried prior to mixing, stripping of asphalt (removal from the pavement) will not take place in hot-mixed, hot-laid asphalt pavements.

A *cold-mixed, cold-laid bituminous paving mixture* is coarse aggregate, fine aggregate, or a mixture of coarse and fine aggregates, with or without mineral filler, uniformly mixed with bitumen (emulsified asphalt, cutback asphalt, or tar) and laid at or near ambient temperature. Note that the mixing is done at normal temperature and drying of aggregates is not necessary except when the particles have surface moisture. To improve bonding, commercial additives are needed in this type of concrete. In winter months, some beating of both the aggregates and the asphalt may be required.

A bituminous surface or base course produced by mixing aggregates and cutback asphalt, emulsified asphalt, or tar at the job site is called *road mixed* or *mixed in place*. A mixture of aggregates and cutback asphalt, emulsified asphalt, or tar prepared at a central mixing plant and spread and compacted at the job site at or near ambient temperature is called *plant-mixed, cold-laid*.

Road-mixed or mixed-in-place asphalt is prepared at the job site using travel plants, motor graders, or other road mixing equipment. The aggregates may consist of open or dense-graded aggregates, sand, or sandy soil. The liquid asphalt is generally heated to a temperature that will provide the necessary viscosity. This type of mix is of lower quality than hot-mixed, hot-laid concrete.

A number of additives are used in the manufacture of asphalt concrete. Asphalt rubber (crumb rubber), which is a recycled product from old tires, is used in hot-mixed asphalt pavements to improve the binding property of aggregates. About 1 to 5% rubber can also increase the viscosity and softening point. Issues of worker safety and the long-term effects of rubber on environment remain to be addressed. Polymers (manufactured rubber) are added to asphalt to produce polymer-modified asphalt. Most commonly, ethyl vinyl acetate (EVA) is added for better dispersion of materials. This compound is also found to increase ductility and adhesiveness. Other polymers used in pavement construction are latex, silicone, and epoxies.

Glasphalt is the term used to describe asphalt that is partly replaced by glass. Sulfur is added to asphalt concrete to provide higher stiffness at elevated temperatures. Fibers are added (asbestos or polypropylene) to improve fatigue resistance and decrease thermal cracking. Carbon black pellets are added as a reinforcing material which increases the pavement durability. Sewage sludge ash and roofing shingle waste have also been recycled in asphalt. Adding hydrated lime to hot mixes increases the strength and stability of the mix while making them more water resistant. Lime also reduces swell, water absorption, and stripping and allows for faster compaction.

6.7 ASPHALT PAVEMENT

Asphalt pavement or flexible pavement is a pavement that has sufficiently low bending resistance to maintain intimate contact with the underlying structure or base, yet has the required stability to support the traffic loads. Its function is similar to that of a bed that provides good contact with the body, yet supports the load without a failure. A number of pavements, such as crushed stone, gravel, and all bituminous types not supported on a rigid base, fall into this category.

Most flexible pavements are constructed with an asphaltic concrete surface layer placed over a treated or untreated base layer or base course and an untreated subbase layer (Fig. 6.6). The advantage of asphalt concrete pavement is that it is able to adjust more readily to differential settlement likely to occur when the roadway is constructed on relatively flexible (or variable quality) soil or ground. In addition, this type of pavement can be repaired and recycled quickly and easily.

But the disadvantage is that the flexible pavement requires a higher level of maintenance than that needed for portland cement concrete pavement (called *rigid pavement).* Moreover, asphalt concrete requires surface treatment, due to hardening of asphalt with age. It was explained earlier that asphalt tends to become hard and brittle with age and under load. The hardening is caused mainly due to oxidation (combining with oxygen in atmosphere). Oxidation is more severe at higher temperature and in thin films. It can be minimized by keeping the number of air voids in the mixture low and by coating the particles thickly.

Asphaltic concrete pavement is constructed with a proper mixture of aggregate particles and asphalt cement. The amount of asphalt cement is crucial to a good performance rating. More asphalt than required results in less than the minimum amount of air space, and similarly, a less than required may result in a high amount of air space. A large number of air voids (more than 6%) may cause early hardening of the asphalt cement from weathering (oxidation and volatilization), leading to failure. A low asphalt content will also produce a brittle pavement.

The amount of asphalt cement generally lies between 3½ and 12% of the total weight of the materials. When the maximum aggregate size is reduced, the percent of asphalt cement increases. For example, aggregates of maximum size ¾ in. (10 mm) are required to have asphalt cement in the range 5 to 12%, whereas 1-in. (25 mm) maximum aggregate has a limit of 3 to 9%.

6.7.1 Elements of Flexible Pavement

A flexible pavement consists of four elements:

- Subgrade
- Subbase course
- Base course
- Surface course

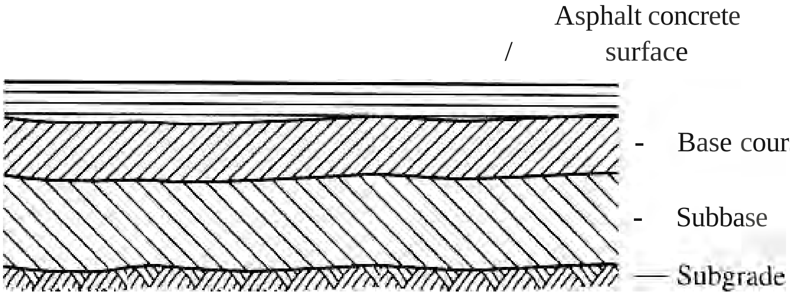


Figure 6.6 Asphalt concrete pavement.

A *subgrade* (also called *prepared roadbed)* consists of natural soil or imported soil, such as in an embankment, improved by stabilization. *Stabilization* is done using various techniques and materials, such as mechanical stabilization and chemical stabilization. The most common stabilization is by adding portland cement. When the native soil is not found suitable to carry loads, it will be stabilized. The subgrade acts as the foundation for the road and should possess good resilient modulus. The *resilient modulus* represents the ability to carry load under repeated application of axial load. It is a measure of the elasticity of roadbed soil or other pavement material.

A *subbase* is a layer between the subgrade and the base course. It is made using materials that are generally superior to that of subgrade. When the subgrade material possesses properties that makes it suitable as a subbase, the subbase layer is omitted.

The material for a subbase consists of particles of various sizes. Up to a maximum of 12% is made up of particles passing sieve No. 200. Lime-treated subbase is aggregate base mixed with lime. Aggregate subbase which may consist of more than one layer is the most economical form. Note that when the normal design process results in a thin layer of subbase, the subbase can be eliminated in place of a thick base layer.

A *base course* (or base layer) is a layer directly beneath the wearing surface. It can be constructed as an asphalt concrete base (called asphalt base course) or as an untreated aggregate base. Aggregate may be one or more of crushed stone, crushed slag, gravel, sand, or combinations of these materials. The base layer can also be constructed using cement-treated (base) aggregates.

In addition to portland cement, a combination of portland cement, pozzolan material, lime, and other cementing agents can be combined with aggregates or soil for construction of the base course and subbase layer. Use of these types depends on the relative cost, availability of materials, type of native material, environmental conditions, and traffic. The base layer is generally identified by the type of material:

- Aggregate base
- Asphalt cement base
- Asphalt-treated permeable base
- Cement-treated base
- Cement-treated permeable base
- Lean concrete base

Cement-treated permeable base is a highly open-graded mixture of coarse aggregate, portland cement, and water placed as the base layer to provide drainage of the pavement section as well as structural support. *Asphalt-treated permeable base* course consists of a mixture of coarsely graded aggregate and asphalt cement. The permeable base courses are commonly used to provide drainage of the pavement section as shown in Fig. 6.7. In a permeable base course, up to about 80% of the aggregate particles are of size equal to or larger than ¾ in. (10 mm).

A *full-depth asphalt concrete* is pavement using asphalt mixture for all courses above the subgrade. This type of pavement consists of little or no aggregate base or

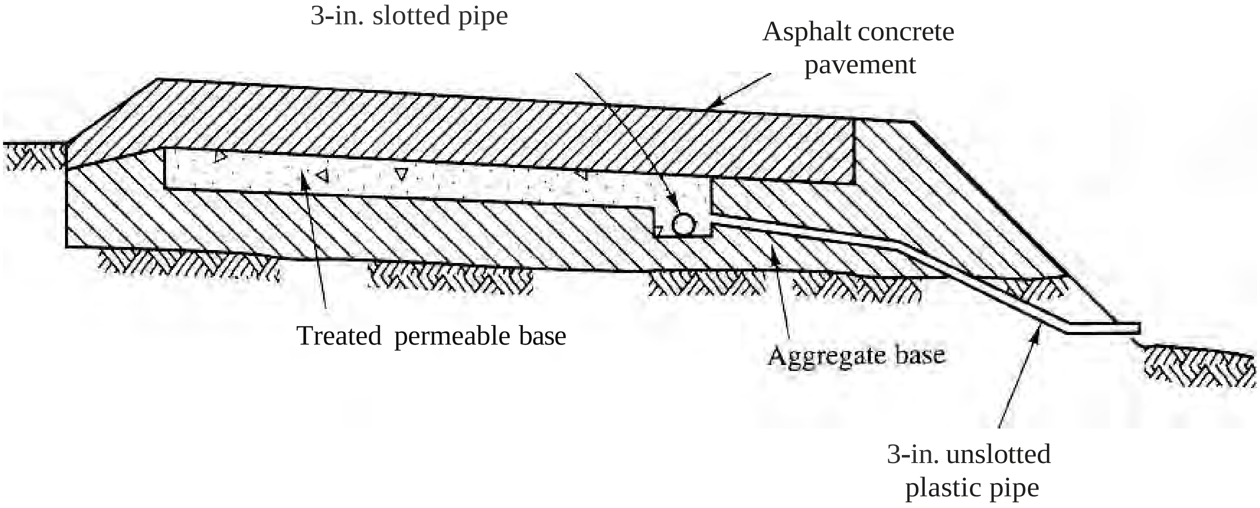


Figure 6.7 Treated permeable base pavement.

subbase. Full-depth asphalt concrete provides a faster method of building flexible pavements. It is generally thinner than the layered pavement and thus requires less excavation of soil.

6.8 SPRAY APPLICATIONS

There are four common spray applications to pavements:

- Surface treatments and seal coats
- Fog seal
- Prime and tack coats
- Slurry seal

Asphalt surface treatment and *asphalt seal coats* are spray applications of asphalt followed by an application of aggregate (stone chips or fine aggregate) embedded by rolling. A single application of asphalt and aggregate is called a seal coat. A surface treatment may consist of single or multiple applications of asphalt and aggregate placed one on the other. In the case of a single application, the thickness of the resulting layer (generally not exceeding ½ in. or 12.5 mm) corresponds to the nominal aggregate size. When multiple applications are used, the thickness of the layer is only slightly larger than the thickness of the finish course and may be as much as 2.5 in. (63.5 mm).

Seal coats and surface treatments provide a waterproofing layer on a base course and improve the skid resistance of the existing pavement. They also extend the service life of a weathered surface and are cost-effective. They are used on an existing surface that is cracked or oxidized to improve the texture and waterproofing, or on a new surface.

Aggregates for seal coat and surface treatment consist essentially of one-size material, and the maximum size is generally not more than twice the smallest size. For example, for ½-in. (12.5 mm) maximum size aggregate, about 95% of the particles pass a ½-in. (12.5 mm) sieve and 30% pass a ½-in. (10 mm) sieve. Nearly 90% of aggregate particles are within ½- and ¼-in. (12.5 and 6.3 mm) sieve sizes. If the size difference is large, the larger particles may be dislodged by the traffic, and the smaller particles lead to "fat" spots. The shape of the particles should be angular.

Fog seal is a light application of a slow-setting emulsified asphalt (diluted with additional water) without the mineral aggregates. The purposes of fog seal are to provide an impermeable layer to the pavement and prevent movement of aggregate particles downward.

A *prime coat* is the application of a liquid asphalt to an untreated foundation layer or subgrade of stabilized soil, gravel, or water-bound macadam. Its function is to coat and bind loose particles and to provide adhesion between the base and the wearing surface. The prime coat also helps to consolidate the surface on which the new treatment is to be placed and prevents the upward migration of capillary water.

Liquid asphalts and road tars of low viscosity can be used for the prime coat. The application should be to a clean surface that is dry or slightly damp and when the temperature is above 55°F (13°C).

A *tack coat* is a thin coat of bituminous material applied to an existing surface (asphalt concrete or portland cement concrete) to provide a bond between the new construction (overlay) and the existing surface. Emulsified asphalt, diluted with additional water, is commonly used. The surface on which the tack coat is applied can be bituminous, portland cement concrete, brick, or stone. Tack coat is the first step in the construction of a new asphalt wearing surface and requires a clean and dry or slightly damp surface. It should be noted that both prime and tack coats are not wearing surfaces themselves.

Slurry seal is a mixture of a slow-setting emulsified asphalt, fine aggregate, mineral filler, and water, applied to the pavement surface without heat. The slurry (binder and other components) penetrates cracks and seals them. It also gives a new surface to the street. The application rate can vary between 4 and 12 lb/yd^3.

Slurry seal is used primarily as a maintenance material for light-traffic roadways mainly to seal the surface cracks on asphalt concrete pavements. Its application helps to fill voids, maintain a minimum wearing surface, and correct surface erosion conditions. Slurry seal is also employed to provide a new wearing surface.

Aggregates for slurry seal may consist of sand, slag, and crushed fines. The amount of asphalt emulsion to be blended with the aggregates is as determined by laboratory mix design. Water is added as necessary to obtain a fluid, homogeneous consistency. Mineral fillers such as portland cement, lime, and fly ash are often added to the slurry.

A *chip seal* is a high-viscosity emulsified asphalt surface coat incorporating rolled-in-rock screenings (chips) over an asphalt concrete pavement (Fig. 6.8).

An *overlay* is a layer of asphalt concrete placed on existing flexible or rigid pavement to restore quality, improve load-carrying capacity, reduce maintenance costs (of highways and vehicles), reduce skid resistance, and extend the service life of the pavement. A nonwoven bonded-fiber synthetic fabric *(pavement reinforcing fabric)* is placed as an interlayer in asphalt concrete overlays to minimize infiltration of surface water. The fabric is also helpful in retarding reflection cracking. Note that the fabric does not add to the strength of the pavement.

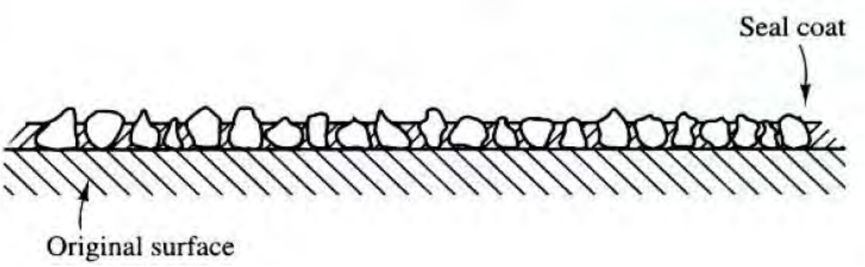


Figure 6.8 Seal coat with crushed stone/gravel cover.

A properly designed overlay can correct a number of deficiencies, such as excessive permanent distress and inadequate ride quality. Using overlays, old roads can be improved in a shorter time at less cost. When one notices excessive permeability, surface roughness, and low skid resistance, overlays may be required.

6.9 TESTING

A number of laboratory tests are described in this section. Following is a list of asphalt properties and the corresponding test numbers.

PROPERTY	TEST NO.
Penetration of asphalt	BITU-1
Ductility of asphalt	BITU-2
Kinematic viscosity of liquid asphalt	BITU-3
Coefficient of viscosity of asphalt	BITU-4

Test BITU-1: Penetration of Asphalt Materials

Purpose: To determine the consistency of an asphaltic material using a penetration test.

Related standard: ASTM D5

Definition:

- *Penetration* is the consistency expressed as the distance in tenths of a millimeter that a standard needle (100 g of total weight) penetrates a sample of the material vertically at 77°F for 5 s.

Equipment: Standard needle [50 mm (2 in.) in length and 1.0 mm (0.0394 in.) in diameter], standard flat-bottomed sample container of metal or glass [55 mm diameter and 35 mm depth, or 3 oz for penetration below 200, and 70 mm diameter and 45 mm depth (or 6 oz) for penetration between 200 and 350] water bath (capacity 10 liter), timing device, thermometer, transfer dish.

Sample: Semisolid or solid bituminous sample.

Procedure:

1. Heat the sample [temperature (90°C + softening point of the sample)] until it is sufficiently fluid to pour.
2. Pour the sample into the sample container to a depth which is 10 mm greater than the depth to which the needle is expected to penetrate when cooled to 77°F.
3. Allow the sample to cool (for 1 to 1½ h for small container and 1½ to 2 h for large container).
4. Place the container in the transfer dish and place it in the water bath at 77°F (25°C). Allow the small container to remain in the water bath for 1 to 1½ h and the large container for 1½ to 2 h.
5. Place the 50-g weight above the needle (total load is 100 g).
6. Cover the container with water from the water bath, and place the transfer dish on the stand of the penetrometer.
7. Position the needle by lowering it slowly until its tip just makes contact with the surface of the sample.
8. Note the reading of the penetrometer dial.
9. Quietly release the needleholder for 5 s.
10. Adjust the instrument to measure the distance penetrated in tenths of millimeter.
11. Make at least three measurements. (Return the sample and transfer dish to the constant temperature bath between the measurements.)

Report: Report to the nearest whole unit the average of the three penetrations whose values do not differ by more than 2 for penetrations less than 50, 4 for penetrations less than 150, 6 for penetrations less than 250, and 8 for penetrations less than 350.

Test BITU-2: Ductility of Asphalt

Purpose: To determine the ductility of asphalt specimen using a briquet test.

Related standard: ASTM D113.

Definition:

- *Ductility* is the distance to which the material will elongate before breaking when two ends of a briquet specimen are pulled apart at a specified speed (5 cm/min) and at a specified temperature (77°F).

Equipment: Briquet mold, water bath, testing machine (specimen is continuously immersed in water), thermometer.

Sample: Asphalt specimen.

Procedure:

1. Assemble the mold on a brass plate.
2. Coat the plate and interior surface of the mold (side pieces only) with a thin layer of a mixture of glycerin and dextrin, talc, or china clay (kaolin) to prevent sticking.
3. Heat the sample until it is sufficiently fluid to pour.
4. Strain the sample through a No. 50 (300-m) sieve.
5. Pour the sample into the mold until it is more than level full.
6. Let the sample cool to room temperature for 30 to 40 min.
7. Place it in the water bath (at 77°F) for 30 min.
8. Cut off the excess bitumen with a hot straight-edged putty knife to make the mold just level full.
9. Place the brass plate and mold in the water bath (77°F) for a period of about 90 min.
10. Remove the briquet from the plate, detach the side pieces, and test immediately.
11. Attach the rings at each end of the clips to the pins or hooks of the testing machine, and pull the end clips apart at a speed of 5 cm/min until the briquet ruptures (thread has no cross-sectional area).
12. Measure the distance in centimeters through which the clips have been pulled.

Report: Report the ductility in centimeters.

Test BITU-3: Kinematic Viscosity of Liquid Asphalts

Purpose: To determine the kinematic viscosity of cutback or other liquid asphalt using reverse-flow viscometers.

Related standard: ASTM D2170.

Definitions:

- *Kinematic viscosity* is the ratio between the viscosity and the density of a liquid. The standard measuring unit is the centistoke (equal to 1 mm^2/s).
- *Density* is the mass per unit volume of a liquid. The standard unit is 1 g/cm3.

Equipment: Reverse-flow viscometer, thermometer, bath, timer.

Sample: Sample of liquid asphalt that is thoroughly mixed. If the sample is too viscous, place it in the tightly sealed container in a bath or oven maintained at about 145°F (63°C) until it becomes sufficiently liquid for stirring.

Procedure:

1. Maintain the bath at a temperature of about l40°F (60°C).
2. Preheat the clean, dry viscometer.
3. Charge the viscometer (following the recommendations of the manufacturer). Allow the charged viscometer to remain in the bath long enough to reach the test temperature (between 10 and 30 min).
4. Start the flow of asphalt in the viscometer.
5. Measure (to within 0.1 s) the time required for the leading edge of the meniscus to pass from the first timing mark to the second (more than 60 s).
6. Clean and dry the viscometer.
7. Calculate the kinematic viscosity to three significant figures using the following equation:

$$\text{Kinematic viscosity, cSt} = C \times t$$

where C is the calibration constant of the viscometer in cSt/s (ASTM D2170) and t is the efflux time in seconds.

Report: Report the test temperature and kinematic viscosity in centistoke.

Test BITU-4: Viscosity of Asphalt Using Capillary Viscometer

Purpose: To determine the viscosity of asphalt cement using capillary viscometer.

Related standard: ASTM D2171.

Definitions:

- *Viscosity* is the resistance to flow of a liquid.
- *Coefficient of viscosity* (also called *absolute viscosity)* is measured as the ratio between the applied shear stress and the rate of shear. The cgs unit, 1 g/cm-s, is called *poise* (P).
- When the ratio between the shear stress and the rate of shear is not constant the liquid is called *non-Newtonian.*

Equipment: Capillary-type viscometer, thermometer, bath, vacuum system, timer.

Sample: A minimum sample of 20 mL of asphalt cement in a suitable container and heated to about 275°F (J 35°C). Constant stirring may be required to prevent local overheating and to release entrapped air.

Procedure:

1. Maintain the bath at 140°F (60°C).
2. Select a clean and dry viscometer that will give a flow time greater than 60 s, and preheat to about 275°F (135°C).
3. Charge the viscometer by pouring the prepared sample to within ±2 mm of fill line E (refer to the viscometer).
4. Place the charged viscometer in an oven or bath maintained at about 275°F (135°C) for a period of about 10 min.
5. Remove the viscometer from the oven or bath, and insert it in a holder. Position the viscometer vertically in the bath so that the uppermost timing mark is at least 20 mm below the surface of the bath liquid.
6. Establish a 300 Hg vacuum below atmospheric pressure in the vacuum system and connect the vacuum system to the viscometer with the toggle valve or stopcock closed. Maintain the vacuum for 30 min.
7. At the end of 30 min, start the flow of asphalt in the viscometer by opening the toggle valve or stopcock.
8. Measure, within 0.1 s, the time required for the leading edge of the meniscus to pass between successive pairs of timing marks.
9. Clean and dry the viscometer.
10. Calculate the viscosity using the following equation:

$$\text{Viscosity, } P = K \times t$$

where K is the selected calibration factor in P/s and t is the flow time in seconds.

Report: Report the test temperature and vacuum with the calculated viscosity value in poise.

CHAPTER 7

Iron and Steel

Historical records and ancient sites show worldwide use of iron and steel during second and third millennia B.C. Many historians think that the center of origin of steelmaking can be placed in India. The Hyderabad province and TiruchirapalJy in India are considered to have been the centers of production of steel more than 3000 years ago. Iron ore was heated with charcoal, and the spongy metal thus obtained was drawn and worked by hammering to make wrought iron. Small pieces of wrought iron and carbonaceous matter were heated at high temperature in crucibles lined with clay. Resulting impure steel was heated and hammered to remove impurities and was marketed in the form of round cakes a few inches in diameter, known as wootz steel.

The technique of ironworking also existed in Asia Minor. Philistines (sea people from whose name comes the word "Palestine") were skilled ironworkers. Iron plow tips made it possible to till heavy soil in Palestine. The use of iron also improved the productivity of workers. Ingots of steel from India were taken to Damascus, where Syrian ironworkers made them into sword blades. This popularized Damascan (damaskene) knives and swords.

Knowledge of iron smelting became common around 1200 B.c. The Chinese are known to have used iron plows around 500 B.C. Iron bars were used around 400 B.C. in Europe as currency, employed as a barter medium for cattle, land, and so on. The iron pillar of New Delhi [16 in. (40.6 cm) in diameter and about 16 ft (4.8 m) in height], which is nearly 1500 years old, is thought to have been made with wrought iron. One of the early uses of cast iron was to make church bells and guns. Iron was also used in transportation. One of the Chinese monks who visited India around A.D. 400 had described seeing suspension bridges held up by iron chains.

The first iron produced in the United States was at Saugus, Massachusetts, in 1645 using ironworkers brought over from England. The iron was used to make plows, tools, and swords, and of course, nails. By about 1770, some 30,000 tons of iron was being produced in the United States annually. A machine to make cold-cut nails was invented in 1777. Introduction of rail transportation opened up huge new markets for the iron and steel industry.

During the 1860s an Englishman, Henry Bessemer, invented a method of converting iron to steel. Adaptation of this process set American steel interests in head-to-head competition with British steel. The first steel rails were produced commercially in Johnstown, Pennsylvania, in 1867. Steel rails helped the nation move forward industrially.

New steel structures and products began to proliferate. Production of high-tensile steel wire made it possible to build suspension bridges. Demand for steel for use in naval ships increased the number of steel plants. The development of universal mills that could roll wide-flange structural sections during the beginning of the twentieth century revolutionized the building industry. Around the same time the auto industry started to expand, further increasing the demand for steel. The post-World War II era continued the large-scale production of steel that helped to rebuild war-torn countries. Today, steel is produced in rebuilt or new plants that are totally modem, efficient, and use computerized equipment.

Steel is now used in countless products, from the heaviest machines and structures to paper clips and watch springs. Using steel, sheets, bars, angles, wide-flange beams, heavy structural products, joists, decks, screws, bolts, bearings, metal buildings, and other construction products are manufactured. Steel is one of the most versatile of human-made construction materials.

7.1 IRON

The basic constituent of steel is iron. Iron is widely available all over the world but only in combination with other elements. Next to aluminum, iron is the most abundant metallic material in the earth's crust (about 4 to 5%). It is found in the form of ores as oxides, carbonates, silicates, and sulfides.

The most important iron-bearing minerals or iron ores are *hematite* and *magnetite.* Hematite (Fe_2O_3), the most commonly used ore. contains about 70% pure iron. Its specific gravity varies between 4.5 and 5.3.

The mined ore is crushed to small particles of size l in. (25 mm) or smaller. These particles are further reduced to fine powder, which is later converted to pellets or sinters. Sintering is a process of application of heat that results in the conversion of fine ore into hard and porous Jumps [size 0.4 to 2 in. (10 to 50 mm)]. *Pelletizing* is a process of forming balls [0.4 to 0.8 in. (10 to 20 mm) in diameter] in the presence of moisture and additives such as bentonite or lime. (Bentonite is a fine-grained plastic clay that is water absorbent.) When powdered limestone is incorporated in the pellets, fluxed *pellets* result.

Blast furnace. Iron is presently produced in a blast furnace, developed in Europe around 1400. At that time, the hot metal tapped in the furnace and cast in sand was designated a "pig" if the weight was less than 112 lb (50.7 kg). From this, the term *pig iron* was derived, which represents iron produced in a blast furnace.

A *blast furnace* is a tall circular shaft that increases in cross-sectional area from the top to the base (Fig. 7.I). The inside of the furnace is lined with firebricks or carbon bricks. A tapping hole is located at a height of about 2 to 3 ft (0.6 to 0.9 m) from the furnace bottom. The main function of the blast furnace is to reduce the ore to metal, followed by separation of the metal from the impurities.

The iron ore in the form of pellets or sinters is charged into the furnace with coke and limestone (Fig. 7.2). *Coke* is a carbonaceous solid produced from coal (bituminous), petroleum, or other raw materials by thermal decomposition. It is generally produced by heating a mixture of coal in the absence of air (in coke ovens). It is charged into the furnace as pieces [0.8 to 3.2 in. (20 to 81 mm) in size]. Limestone is added to act as a flux that holds the silica and alumina impurities of the ore and coke. Dolomite with or without limestone can also be used as a flux.

A powerful air blast through the bottom raises the temperature sufficiently to burn coke, melt iron, and burn off oxygen. As the charge comes to the bottom of the furnace, the temperature increases to about 3000°F (1650°C), which is enough to melt the iron. The molten iron, which has a high carbon content, is collected at the bottom of the furnace every few hours. It flows into hot metal cars, which transport it to the steelmaking furnace.

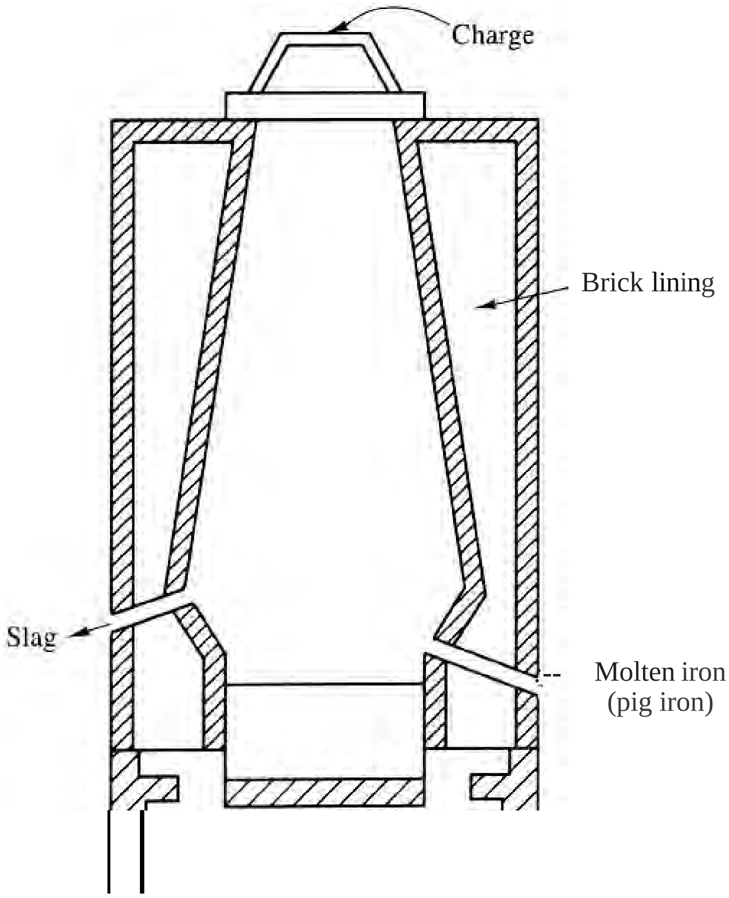


Figure 7.1 Schematic view of blast furnace.

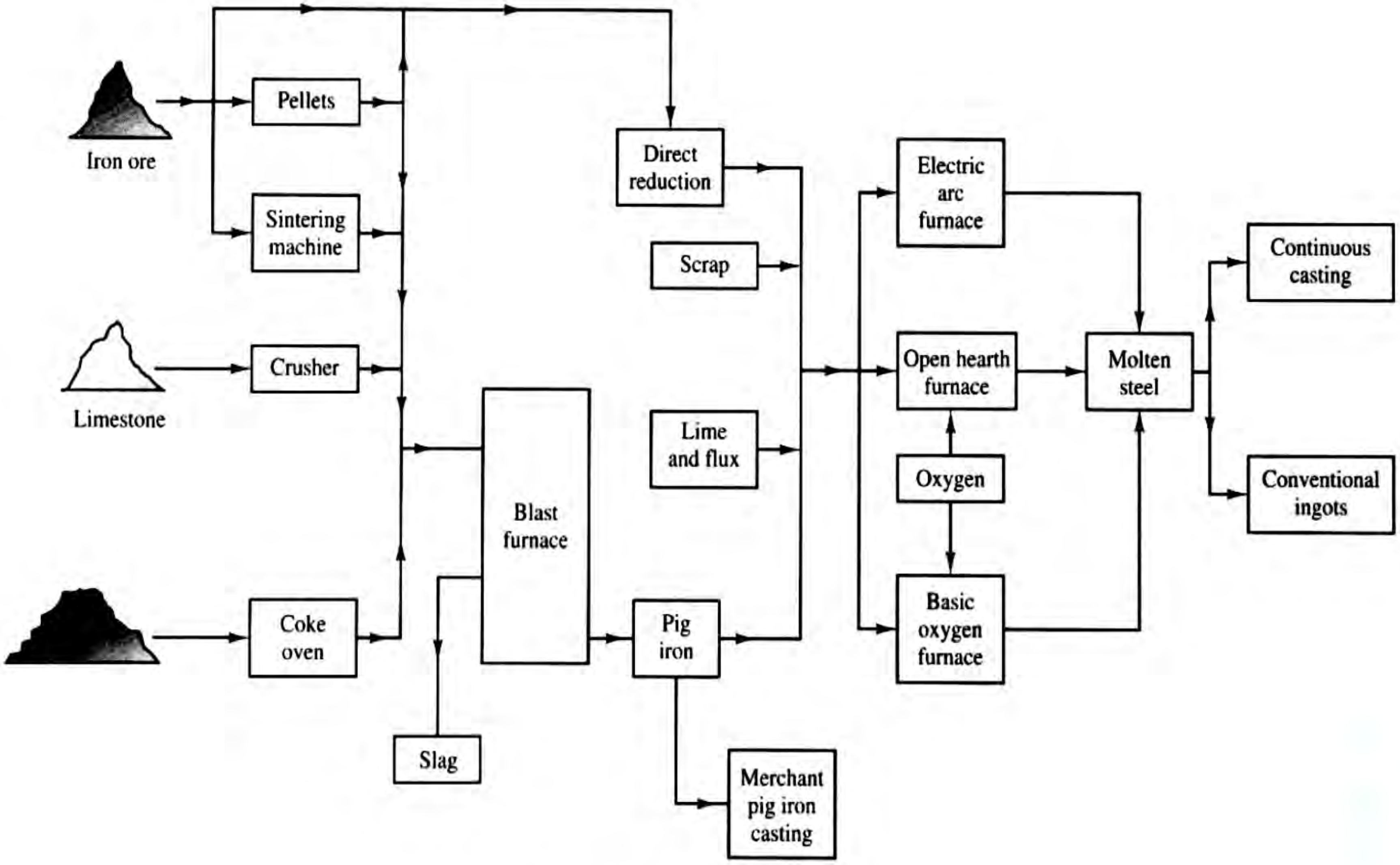


Figure 7.2 Steelmaking process.

A nonmetallic product, consisting essentially of silicates and aluminosilicates of calcium and other bases, is produced simultaneously with the molten metal. This product, called slag (or fluid slag), floats to the top and is also collected at the base of the furnace. It is diverted to slag pits or pots for further processing. Pulverized or crushed slag is used in the manufacture of special cements.

As noted earlier, pig iron tapped every 4 to 6 hours, runs to hot metal cars for conveyance to the steelmaking location. When pig iron castings are required, it is run into a pig-casting machine. At present, most pig iron is made into steel; the balance goes to make cast iron.

Pig iron is not pure iron; it is metal nearly saturated with carbon (taken from the coke). In addition, pig iron contains manganese, silicon, and other materials. The type and constituents of pig iron depend on the composition of the ore.

7.1.1 Cast Iron and Wrought Iron

Iron products come in three commercial forms (Table 7.1):

- Wrought iron
- Steel
- Cast iron

Wrought iron has the least carbon, and cast iron has the most carbon. An increase in the amount of carbon decreases the melting point of the metal. In fact, carbon exerts the most significant effects on the microstructure and properties of iron products. The upper theoretical limit of carbon in steel is 1.7%; in structural steel the carbon content is generally less than 0.25% (by weight).

TABLE 7.1 SOME PROPERTIES OF IRON-BEARING METALS

Material	Carbon content (%)	Silicon (%)	Manganese (%)	Melting point [°F(C)J	Tensile strength [ksi(MPa))	Tensile modulus [ksi(GPa)
Pig iron	3.5 .5	1-2	0.25-1	3040 (1670)		
Pure iron	0.01-0.02	<0.01	0.01-0.02	2795 (1535)	49 (335)	
Wrought iron	0-0.1	0.1-0.2	<0.1		45-55 (310-380)	29 X 10^3 (200)
Mild steel	<0.25	0.05-0.25	<0.68	Varies with carbon content	65 (450)	3 X l0^3 (207)
High-carbon steel	1.4	<0.8	<1.5	Varies with carbon content	130 (900)	30 X 10' (207)
Cast iron	5.0	1.25	1-2.5	2084 (I 140)	16 (110)	15-22 X 10^3 (103-152)

Wrought iron. Wrought iron is manufactured by melting and refining iron to a high degree of purity. The molten metal is then poured into a ladle and mixed **with** hot slag. The fluxing action of the slag causes a spongy mass to form which is processed by rolling and pressing. This is wrought iron. It is the only iron-bearing material containing slag (from I to 3% by weight).

Wrought iron can be described as a low-carbon steel (less than 0. I% carbon by weight) containing a small amount of slag, usually less than 3%. The slag is distributed throughout the metal and appears as long fibrous elements, which distinguish this metal from steel with the same carbon content. Wrought iron contains less than 0.1% manganese and 0.2% silicon.

The mechanical properties of wrought iron are nearly the same as those of pure iron. Its ductility is somewhat lower than that of steel. Its tensile strength along the grain varies between 45 and 55 ksi (310 and 380 MPa). Across the grain (transverse to the direction of rolling), the tensile strength is lower.

Wrought iron can be cold-worked, forged, and welded like steel. *Forging* is working a metal to a predetermined shape by one or more such processes as hammering, pressing, and rolling. *Cold working* is working at a temperature that does not alter the structure changes caused by the work or that is below the recrystallization temperature. Wrought iron can be molded easily and has good resistance to corrosion. It is used to make pipes, corrugated sheets, grills, bars, chains, and other products.

Cast iron. *Cast iron* is manufactured by reheating pig iron (in a cupola) and blending it with other materials of known composition. Alternate layers of pig iron (with or without scrap steel) and coke are charged into the furnace. Limestone is added to flux the ash from the coke. Heat necessary for the smelting is supplied by the combustion of the coke with air supplied by the blast. The function of the cupola is to purify iron and produce a more uniform product. When sufficient metal is accumulated at the bottom of the furnace, it is tapped.

Ordinary cast iron is called *gray cast iron,* owing to the color of fracture. When the fracture surface has a silvery white metallic color, it is called *white cast iron.* The amount and form of carbon affect the strength, hardness, brittleness, and stiffness of cast iron. Gray cast iron contains free carbon (graphite flakes), which makes the metal weak and soft. It is the most widely used cast iron. In white cast iron, carbon is combined chemically with iron in the form of cementite (Fe_3C), which makes this metal strong, hard, and brittle. Note that pure iron is a soft and ductile metal. The addition of carbon to iron increases its hardness and the strength, but lowers the ductility. Cast iron has high compressive strength, but its tensile strength is low. Until about I 800, only cast iron columns were used in buildings. Later, cast iron beams were developed. Wrought iron was used in bridges and multistory buildings during 1850s. But by the end of the nineteenth century, steel dominated the bridge and the building construction. Presently, a number of types of steel are produced which find application in nearly all phases of the construction industry.

7.2 STEEL

Steel is a combination of iron and carbon. The carbon content may range between about 0.01 and 1%. The addition of carbon not only hardens the metal but also imparts other distinct properties. Steel also contains varying amounts of manganese (less than J .6%), phosphorus, sulfur, and silicon (less than 0.6%), together with some 20 other alloys. The alloys are added to molten steel to produce steel of different characteristics, such as hardness, tensile strength, and toughness.

Steel is produced in a basic oxygen furnace (BOF), open hearth furnace, or electric arc furnace. Ingredients for the BOF and the open hardens furnace are the same: one or more of molten pig iron, iron ore, mill scale, scrap metal (e.g., junked cars and steel cans), and limestone. Iron ore controls the carbon content and limestone acts as a fluxing agent. The principal ingredient for the electric arc furnace is scrap metal.

A charge consisting of iron-bearing materials is introduced into the furnace (Fig. 7.2). In the basic oxygen furnace, high-purity oxygen is blown at high velocity through the upright furnace to promote rapid oxidation, which is the combination of oxygen with nonferrous elements, especially carbon. This reaction generates enough thermal energy to raise the temperature to the required levels without requiring external fuel to be supplied to the furnace. The oxides either leave the furnace as gases or combine with the slag.

The slag-producing materials (limestone or lime) are added after the oxygen blow. When the molten liquid has reached the specified composition, the furnace is tapped into a ladle. During the tapping, alloying elements are added. Basic oxygen furnaces, largely controlled by computers, can produce a heat of steel in about 45 minutes. At present, BOF is the chief method of producing steel.

An *open hearth furnace* (so named because the charge is open to the surface of flames) utilizes the same raw materials (charge) as in the BOF. The charge is melted through liquid fuel and gas with preheated air for combustion. The flames reduce the amount of unwanted elements such as carbon, manganese, silicon, phosphorus, and sulfur. The oxidizing agent is iron ore.

An *electric arc furnace* is used to produce regular carbon steel grades. These furnaces also allow close control of temperature and refining conditions required in the manufacture of some special steels. The charge consists essentially of scrap metal. Some iron ore and lime are added during the melting process. High-temperature electric arcing generates the high temperatures required for melting and refining the steel.

Modern electric arc furnaces work on 100% scrap, but some use a small amount of cold or molten pig iron. Before the scrap metal is placed in storage, it is screened for contaminants and nonmetallic parts. Desired carbon content in the molten metal is achieved by the addition of coke. Lime is used to remove impurities in the steelmaking.

Various alloying elements are added during tapping of steel. Manganese gives strength and toughness to steel. In structural steel, manganese content is about 1.35%. Silicon provides strength and hardening properties. It is also an oxidizing agent.

Aluminum is added to control deoxidation and for fine graining steel. Chromium is added along with nickel to produce stainless steel. Nickel also gives toughness to the metal. Chromium steels can withstand abrasion and shock very well. Molybdenum is added to improve tensile and hardening properties. The corrosion resistance of steel containing sufficient levels of copper, chromium, nickel, and silicon is superior to that of steels without these elements. Copper increases the tensile properties and hardness but decreases the ductility. Carbon-manganese levels are important to determine the weldability of steel.

7.2.1 Steel Products

The molten steel from the furnace is conveyed through ladles to ingots or goes through a continuous slab caster (Fig. 7.2). The continuous casting converts a heat of molten steel to semifinished products of varying widths, lengths, and thicknesses. The semifinished products come in three types (Fig. 7.3):

- Blooms
- Slabs
- Billets

Blooms are generally square or rectangular in cross section (area greater than 36 in^2 or 232 cm^2) while slabs are flat and wide. *Billets* are, generally, square pieces of steel 4 to

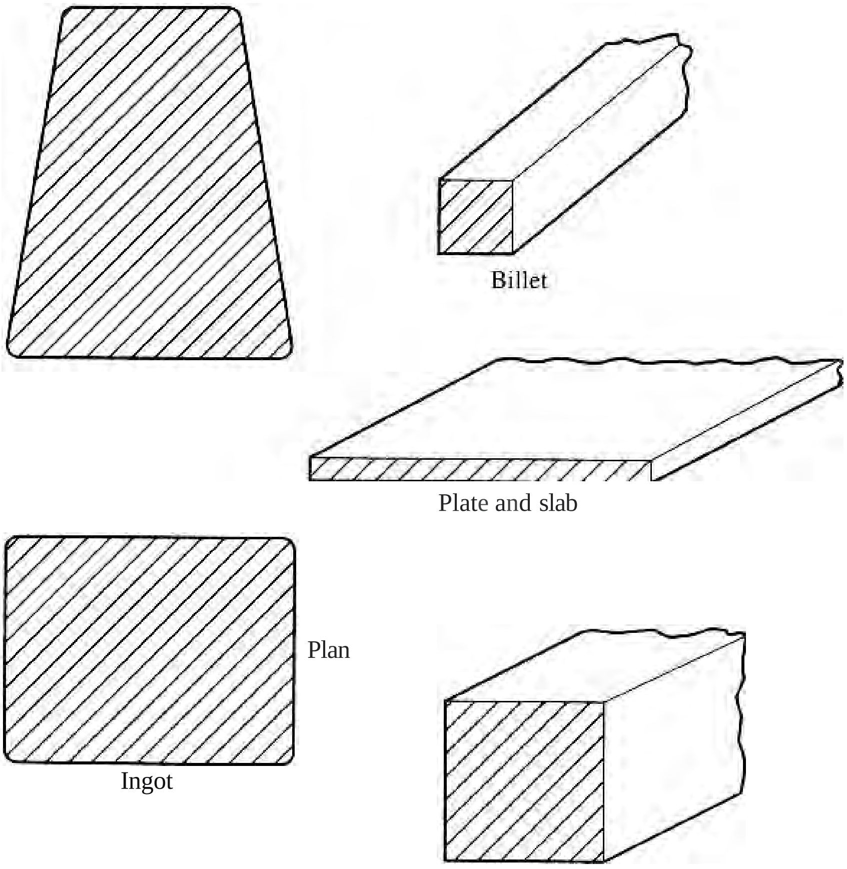


Figure 7.3 Steel products.

6 in. (10 to 15 cm) in cross section which are shipped to rod mills for rolling. Steel rods are produced on the high-speed continuous rod mills from preheated billets.

The procedure of pouring molten steel into ingot molds is called *teeming.* In the ingot molds (usually of cast iron), the molten steel is allowed to cool and the molding is removed. The steel ingots, which weigh between about 10,000 and 100,000 lb (4530 to 45,300 kg), are later heated in special furnaces called *soaking pits* until they attain uniform temperature throughout. Reheated ingots travel to either blooming or slabbing mills, where they are squeezed down to a smaller size so that they can be handled on a finishing mill. Then they are rolled into semifinished products. This conventional casting procedure is time consuming and costly, due to the number of stages involved, additional spaces required for casting, stripping, and reheating, and transportation and handling costs.

In the continuous casting approach, molten steel is poured between a pair of water-cooled flanged rolls so as to solidify it continuously into a thin-rolled strip or sheet. The intermediate stages of first casting the hot steel into slabs or ingots and later gradually rolling the reheated metal into the desired shapes are missing in this operation.

Universal mills are used for rolling wide-flange shapes. Both wide-flange and H-pile sections are generally hot-rolled products. To save time in rolling, structural shapes are also cast continuously. Continuous casting and low carbon levels contribute to improved surface quality. In the continuous-casting approach (using universal roughing and edging mills), steel is cast as a beam blank in a shape that approximates the net shape of the beam. The intermediate milling stage is eliminated in this process. Beams up to 24 in. (61cm) deep are presently cast using this method.

Conventionally, structural shapes and H-piles are produced on structural and shape mills. Standard mills form various shapes by passing reheated (to a uniform temperature) blooms or billets through the mill rolls. Hot rolling involves passing the material between two rolls where the gap between the rolls is lower in height than the material entering. The metal passes repeatedly back and forth through the same rolls to reduce it to the desired thickness and shape. Plain barrel rolls are used for flat products and grooved rolls are used for structural shapes, rounds, and squares.

A cubic foot of steel weighs about 490 lb. The weight of the shapes is calculated from their theoretical dimensions and rounded off to the nearest pound.

Bars are hot-rolled from billets. (Billet mills reduce blooms to billets.) In the bar mill, reheat furnaces bring the billets to rolling temperature. The rolls exert pressure horizontally and vertically to produce twist-free bars. During each pass through the rolls, the metal elongates and is reduced further in cross section. Grooves on the surface of the roller produce the desired bar shape and size. Steel wires and rods are made similarly in rod mills.

Structural tubes are made from large steel coils which are uncoiled at the beginning of a long process line and pulled through a series of forming stands, which shape the flat steel into a round tube. After welding, the tube goes through an air-cooling section, then a water-cooling section, and finally into a sizing section, which finalizes the round shape into other shapes. The tube, which has the desired shape, is cut into the required lengths and discharged into a bundling table. stacked in the required configuration, and banded for shipment.

7.3 PROPERTIES OF STEEL

Steels usually contain less than 1% carbon by weight. Structural steel has less than 0.25% by weight of carbon. Manganese is the principal alloying element and is added when the steel is in molten condition in amounts up to about 1.6%.

Carbon exerts the most significant effects on microstructure and properties of steel. Increase in carbon content increases the hardness, strength, and abrasion resistance, but decreases the ductility, toughness, and impact resistance (Fig. 7.4). Ductility, as measured by the percent elongation during the tension test, decreases drastically with increase in carbon content. Toughness, as measured by the area under the stress-strain diagram, decreases rapidly with carbon content exceeding 0.4 %.

Tensile strength and yield point of steel are maximum when carbon content is about 1%. High-strength low-alloy structural steel (ASTM A572) is expected to have a

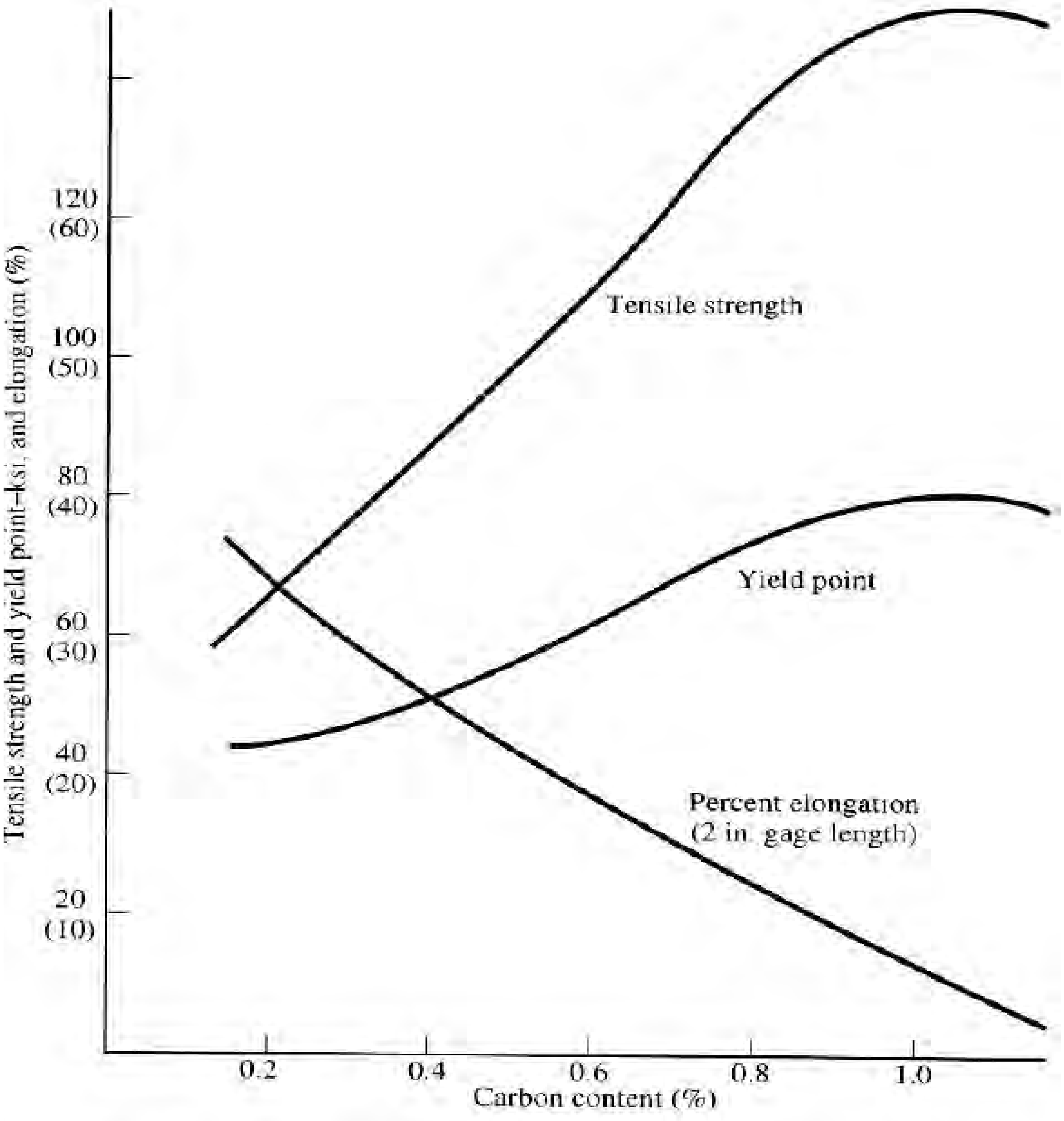


Figure 7.4 Effect of carbon content on mechanical properties of steel.

tensile strength of 60 ksi when the carbon content is 0.2%, and 80 ksi when the carbon content is 0.26%. With heat treatment it is possible to change properties of steel without changing the chemical composition. Ductility is also affected by the heat treatment.

Some of the carbon exists within the crystals of iron (in solution), and most of the balance forms a chemical compound (interstitial or intermetallic compound) with the iron as Fe_3C (iron carbide, combined carbon, or cementite).

Cementite is the hardest and most brittle component of steel and is found in high-carbon steel. It contains 6.67% carbon and 93.33% iron. In structural steel, which contains carbon less than 0.25% by weight, carbon exists mostly within the crystals of iron. *Ferrite iron* (also called *alpha iron)* is the stable form of iron at temperature below 1670°F (910°C), and dissolves carbon in interstitial solid solution to a maximum of 0.08%. Ferrite is the solid solution of carbon in alpha iron and contributes to cold-working properties of steel. Alpha iron is the softest compound in steel and is very ductile.

At 2065°F (1130°C), iron undergoes a polymorphic change to *gamma iron*, which is capable of dissolving carbon to a maximum of 2%. *Austentite* is the solid solution of carbon in gamma iron. It is soft and ductile. At about 2535°F (1390°C), a further polymorphic change takes place and *delta iron* is produced. It has magnetic properties.

In general, properties of steel are greatly affected by three factors:

- Chemical composition
- Heat treatment
- Mechanical work

Carbon and alloying elements affect both physical properties (such as weldability and corrosion) and mechanical properties (such as yield strength, tensile strength, and ductility).

Mechanical properties. Figure 7.5 shows typical stress-strain diagrams of steel in tension. All steels show an initial elastic phase followed by yielding or strain hardening. The elongation or strain at failure depends on the type of steel. The modulus of elasticity of steel, which is the slope of the initial straight-line portion of the diagram, *is* constant, equal to 29,000 ksi (200 0Pa) for all types of steel.

Working steel to obtain desired shapes and sizes affects the stress-strain diagram. *Hot working* is mechanical deformation at temperatures slightly above the transformation temperature, and *cold working* is mechanical deformation at temperatures below the transformation temperature. Cold working increases the strength properties but decreases the ductility.

Yield point is a stress at which there is a marked increase in strain without an increase in stress. Some steels exhibit a sharp knee or discontinuity at the end of the elastic state. Stress corresponding to the top of the knee is the yield point. In steels that do not show marked yielding during the tension test, *yield strength* is measured as stress corresponding to a known strain or an offset (proof stress). In the offset method, a line is drawn parallel to the initial straight-line part of the stress-strain diagram at the prescribed offset value. The stress corresponding to the intersection of this line with the stress-strain diagram is called yield strength.

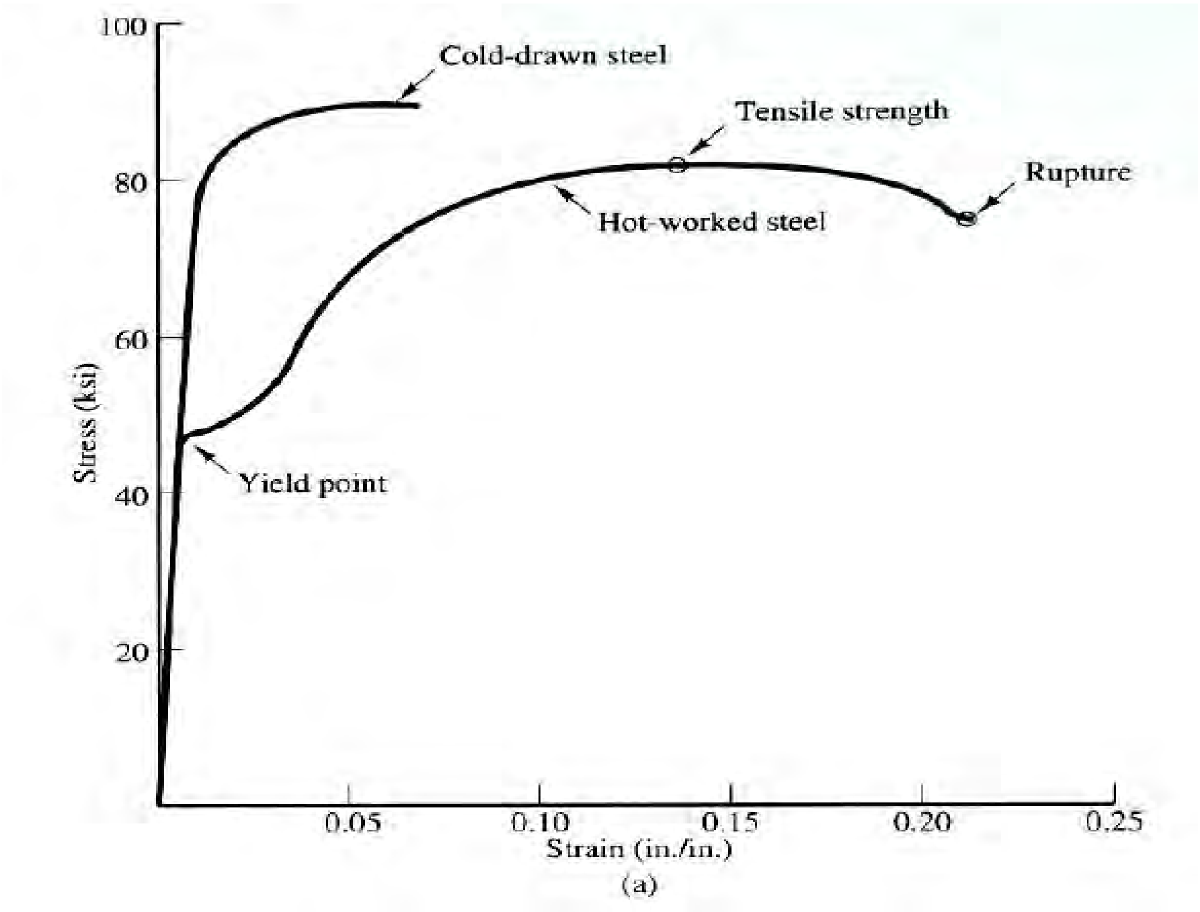


Figure 7.Sa Typical stress-strain diagram of steel.

Notch toughness is a measure that is commonly used to calculate steel's behavior in a ductile or brittle transition range. It is influenced by many factors, such as chemical composition, hot and cold workjng temperatures, internal cleanliness and method of fabrication, carbon content, oxygen level, and grain size.

Properties of steel are greatly affected by elevated temperatures (Fig. 7.6). Very high temperatures [exceeding about 900°F (480°C)] may not only cause loss of cross section but may result in metallurgical changes and severe deformation. Steel exposed to very high temperatures will have heavy scale, pitting, and surface erosion. Exposure to severe fire of nominal duration will destroy the ability of steel members to sustain loads. The modulus of elasticity of steel decreases from 29,000 ksi (200 GPa) at 70°F to about 25,000 psi (172 GPa) at 900°F. Beyond this temperature, the modulus of elasticity decreases rapidly at rugher temperatures.

7.4 STRUCTURAL STEEL

Structural size shapes are rolled flanged sections having one dimension of the cross section equal to or greater than 3 in. (7.5 cm). They are manufactured in many shapes and grades (Fig. 7.7). These products are used as columns, beams, and bracing members in buildings, for trusses, as bridge girders, and in prefabricated structures and similar construction.

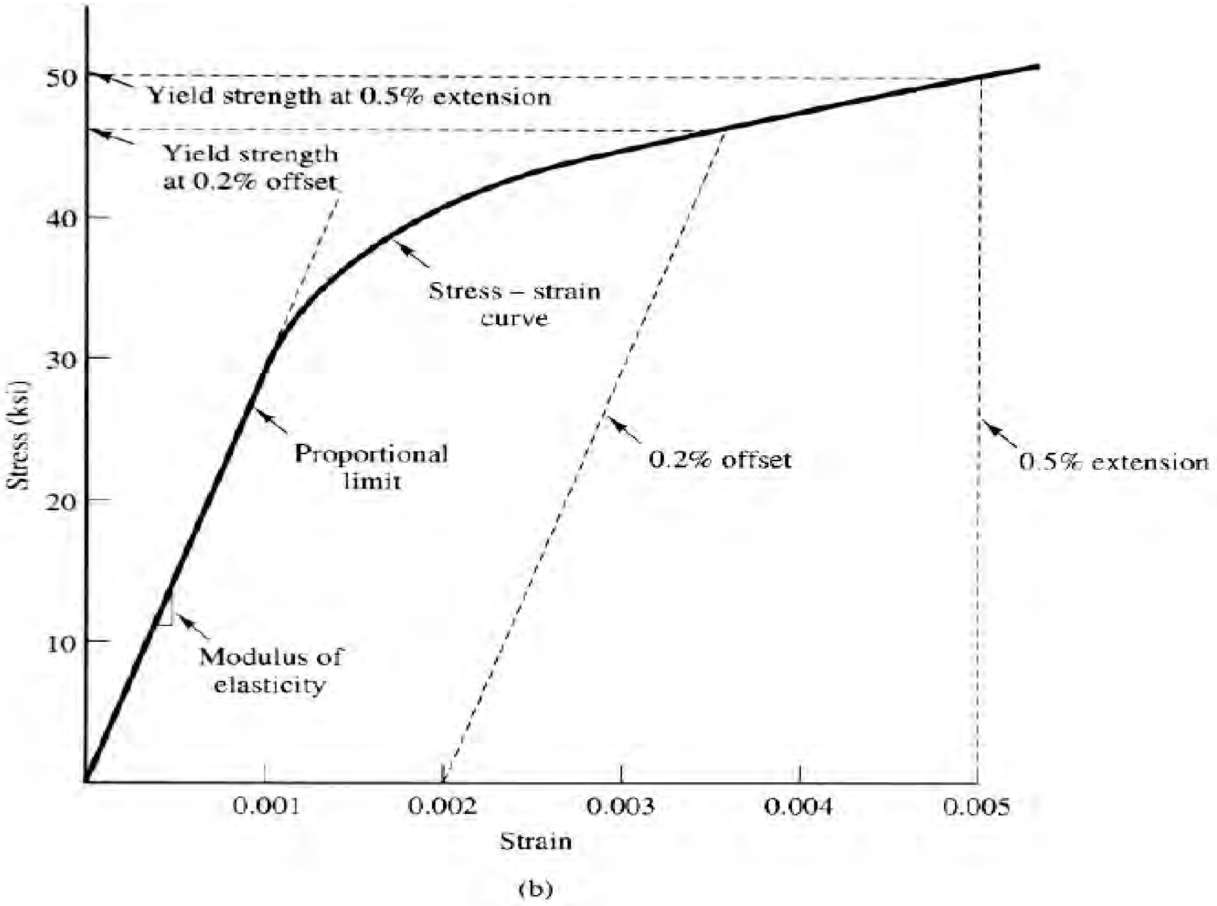


Figure 7.5b Typical stress-strain diagram of yield strength determination.

W shapes are doubly symmetric wide-flange shapes whose inside flange surfaces are substantially parallel (Fig. 7.8). The profile of a W shape of a given nominal depth and weight available from different manufacturers is essentially the same except for the size of fillets between the flange and the web. These shapes can be used as beams or columns.

HP shapes are wide-flange shapes whose flanges and webs are of the same nmninal thickness, and whose depth and width are essentially the same. They are used as bearing piles. *S shapes* are doubly symmetric shapes whose inside flange surfaces have approximately 16.67% slope (or 2 in 12 in.). They are used primarily as beams or girders in building construction. *M shapes* are doubly symmetric shapes which cannot be classified as W, S, or HP shapes.

C *shapes* are channels produced with inside flange surfaces having approximately 16.67% slope (or 2 in 12 in.). *MC shapes* are channels that cannot be classified as C shapes. Both C and MC shapes are available only from a limited number of producers. *L shapes* are equal-leg or unequal-leg angles.

A structural steel shape is designated by a letter followed by two numbers separated by ax. An example is W 8 x 67. The letter (W) identifies the shape. The first number

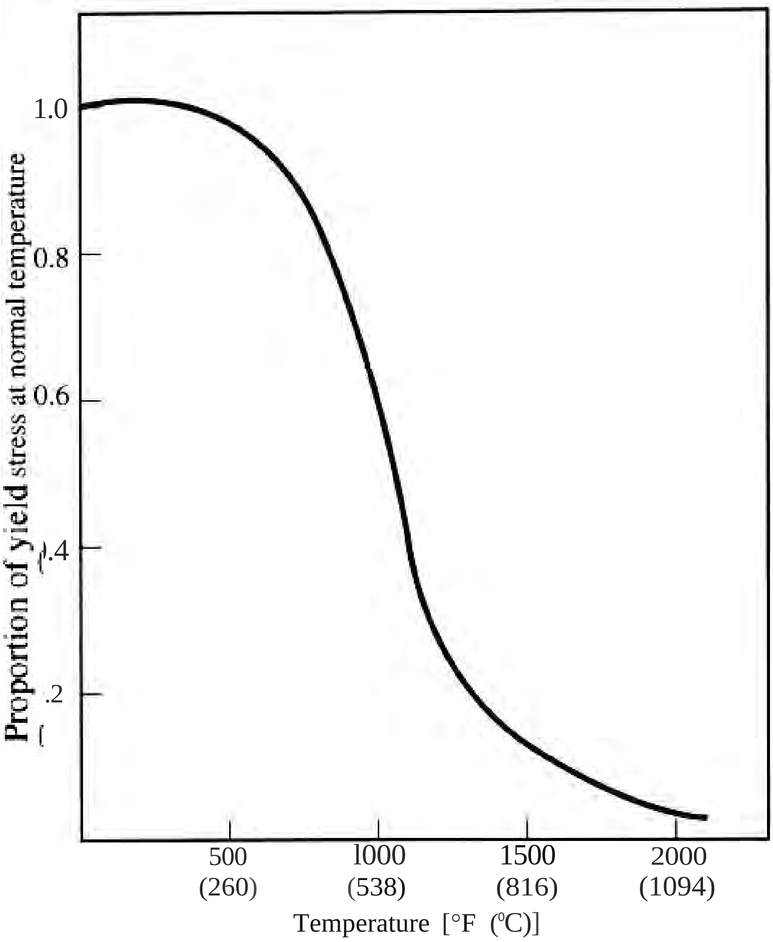


Figure 7.6 Effect of temperature on yield stress of steel (typical).

(8) is the nominal depth of the cross section in inches. The second number (67) is the weight of the member in pounds per linear foot. Note that the nominal depth is not the actual depth of the member; the actual depth can be equal to, more than, or less than the nominal depth. For example, the actual depth of W8 x 67 is 9 in. and that of W8 x IO is 7.89 in. Cross-sectional properties of these structural shapes (such as flange thickness and width, web thickness and width, cross-sectional area, and moment of inertia) are listed in the *Manual of Steel Construction* of the American Institute of Steel Construction (Chicago). The flange thickness listed in these tables for S, M, C, and MC shapes is the average flange thickness. In calculating the theoretical weights, fillets and roundings are included for all shapes except angles.

7.4.1 Structural Grades

Structural steel (hot-rolled structural shapes, plates, and bars) is produced in seven grades: A36, A529, A441, A572, A242, A588, and A514. Chemical and tensile requirements for these grades are shown in Table 7.2. A36/A57250 dual grade is a steel formulated to meet overlapping chemical and mechanical specifications for both **ASTM** A36 and ASTM A572 grade 50 steel. Weldability for this special steel is the same as that of grade 36 steel.

A36 grade, which is called *all-purpose carbon steel* (or *structural carbon steel),* is the most widely used steel in building and bridge construction. A529 steel, called

TABLE 7.2 PROPERTIES OF STRUCTURAL STEEL

ASTM designation	Type	Grade	Chemical requirements (%) Carbon (max)	Manganese (max)	Copper (min)	Tensile requirements Tensile strength [ksi (MPa)]	Yield point min [ksi (MPa)]	Availability
A36	Structural carbon steel	36	0.26	-	0.20	58-80 (400-550)	36 (250)	All plates shapes, and bars
A572	High-strength low-alloy steel of structural quality	42	0.21	1.35	0.20	60(415)	42 (290)	All shapes, sheet piling, and tees
		50	0.23	1.35	0.20	65 (450)	50 (345)	All shapes, sheet piling, and tees
		60	0.26	1.35	0.20	75 (520)	60 (415)	Limited shapes, all sheet piling, and tees
		65	0.26	1.35	0.20	80 (550)	65 (450)	Limited shapes and all trees
A529	Structural steel with 42 ksi min. yield point	42	0.27	1.2	0.20	60-85 (415-485)	42 (290)	Selected shapes, plates, and bars of ½ in. and less in thickness
A441	High-strength low-alloy structural steel	(Discontinued as of 1989; replaced by A572)						
A242	High-strength low-alloy structural steel (corrosion resistant)	42-50	0.15	1.0	0.20	63-70 (435-480)	42-50 (290-345)	Limited shapes, plates, and bars
A588	High-strength low-alloy structural steel with 50 ksi min. yield point (corrosion resistant)	50	0.17--0.19	0.5-1.25	0.2--0.5	70 (485) 63-70 (435-485)	50 (345) 42-50 (290-345)	All shapes Plates and bars
A514	High-yield-strength quenched and tempered alloy steel	90-100	0.12-0.21	0.4-1.10	0.15-0.50	100-130 (690-895)	90-1JO (290-690)	Plates

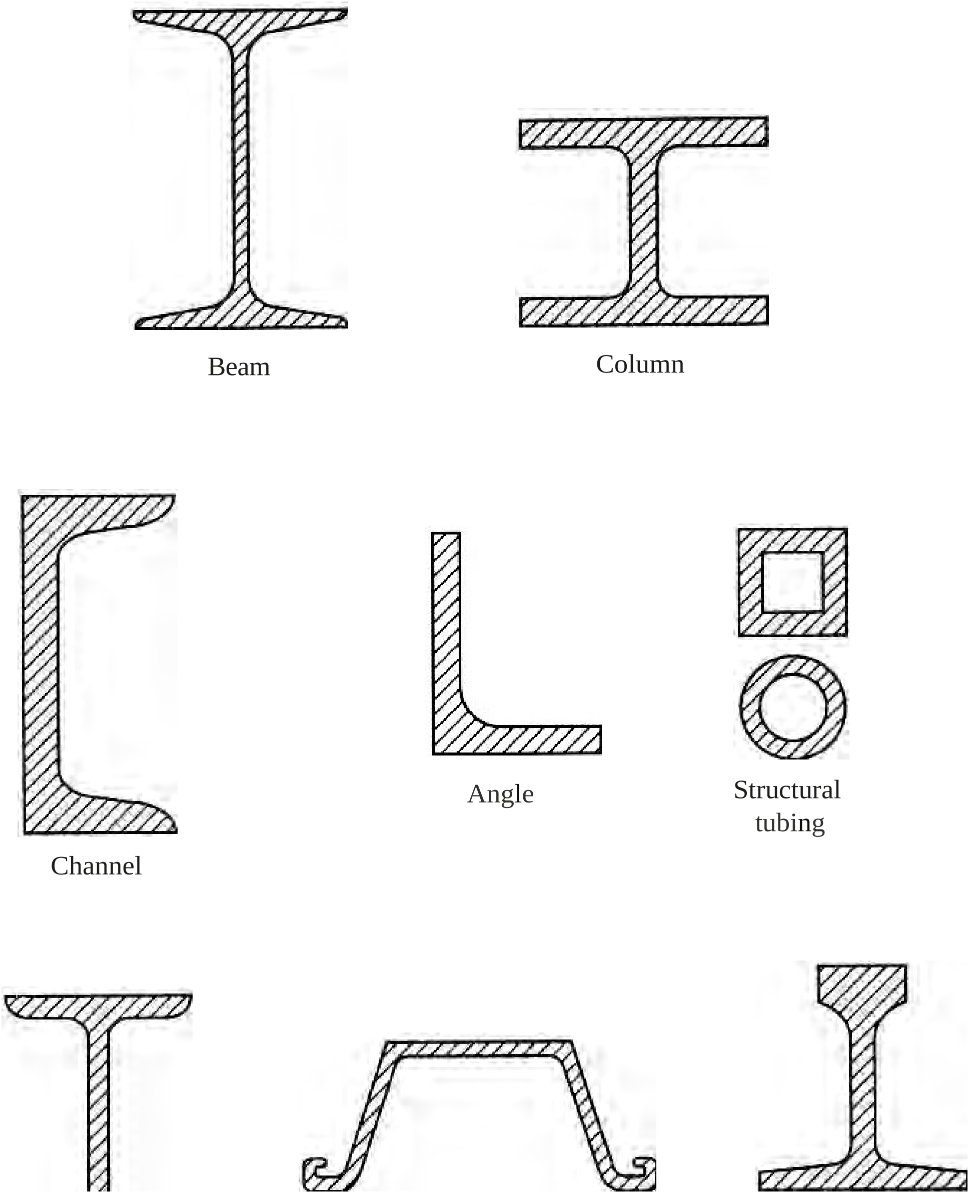
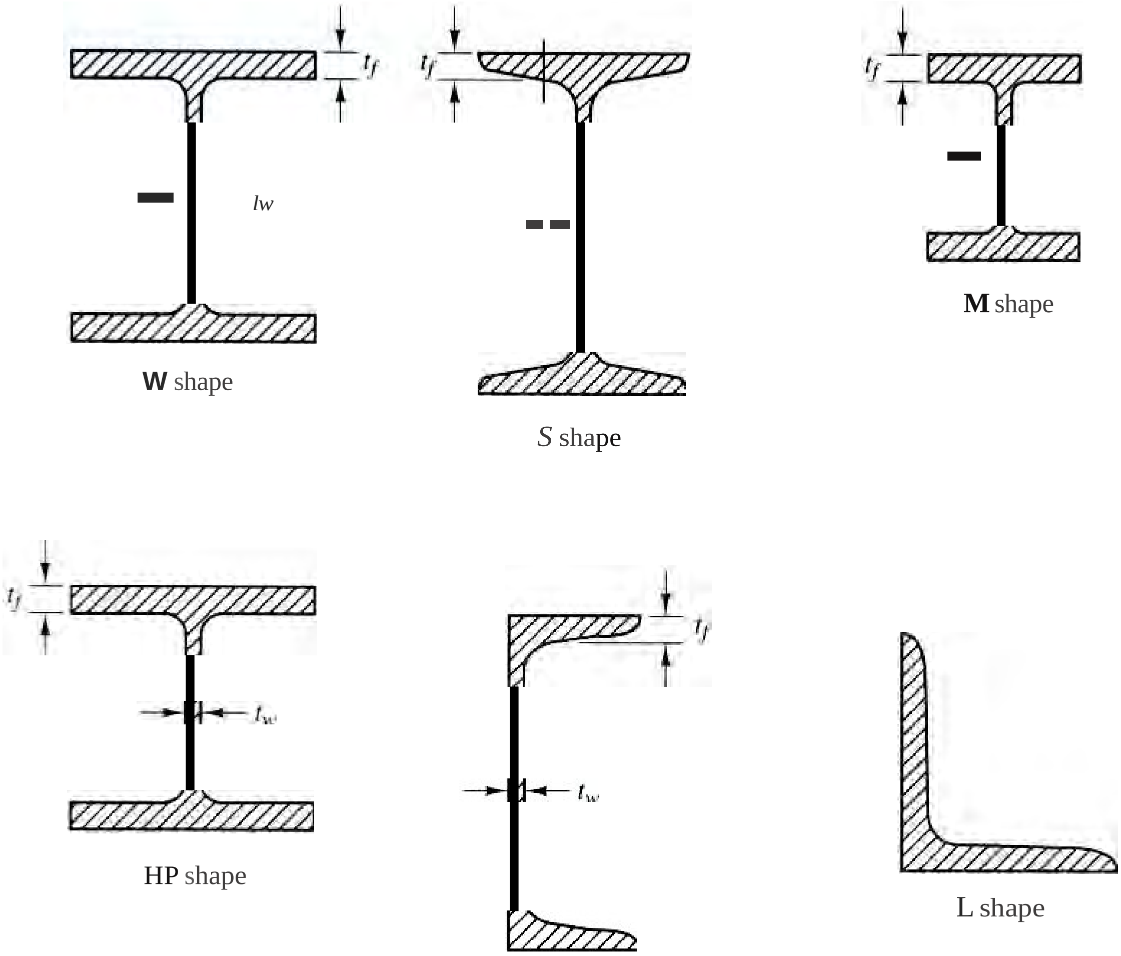


Figure 7.7 Principal hot-rolled sections.

structural carbon steel, has a 42-ksi minimum yield point. Grades A441 and A572 are called high-strength low-alloy structural steel. Grade A441 steel is discontinued from **ASTM** as of 1989. Grades A242 and A588 are atmospheric corrosion-resistant high-strength low-alloy structural steel. Grade A514, quenched and tempered alloy structural steel, is available only as plates.

Carbon steel is the type of steel whose properties are due primarily to the carbon content. The amounts of alloying elements, except manganese, are low. *Alloy steel* is any type of steel in which the amounts of alloying elements exceed certain limits. It owes its distinct properties to elements other than carbon. *High-strength low-alloy steel* is a type of steel that has improved mechanical properties to those of low-carbon steel.

As noted earlier, A36 grade steel is the most commonly used structural steel (Fig. 7.9). It has been used successfully in buildings, transmission towers, bridges, and many



W shape

S shape

M shape

HP shape

C and MC shape

L shape

Figure 7.8 Structural shapes. t_f and t_w are flange and web thicknesses, respectively.

other structures in various temperature conditions. Past experience has shown that this grade of steel can offer satisfactory performance in low temperatures. Brittle fracture is not usually experienced in these structures even at below-normal temperatures.

Design using high-strength steel results in lighter sections and may prove economical, especially for tension members and beams in continuous and composite construction. Grades A588 and A242 can be used in the bare (uncoated) condition in most atmospheres. When these two steels are exposed to normal atmospheric conditions, a tightly adherent oxide will form on the surface. This protects the steel from further atmospheric corrosion. But these two grades of steel can also be coated, and the coating life is typically longer than that for the other steels. The use of the coated steel results in lower maintenance costs over the life span of the structure, although the initial material cost is high.

Failure types. Typical failures in steel construction may be due to yielding of member, failure of connections, and/or buckling of a member. The connection failure is the most common cause of steel building failure. Buckling of columns rarely has resulted in structural collapse. Hot-rolled steel shapes used in the majority of steel buildings are not prone to brittle failure. When fracture occurs by cleavage at a nominal tensile stress that is below yield stress, it is called brittle fracture.

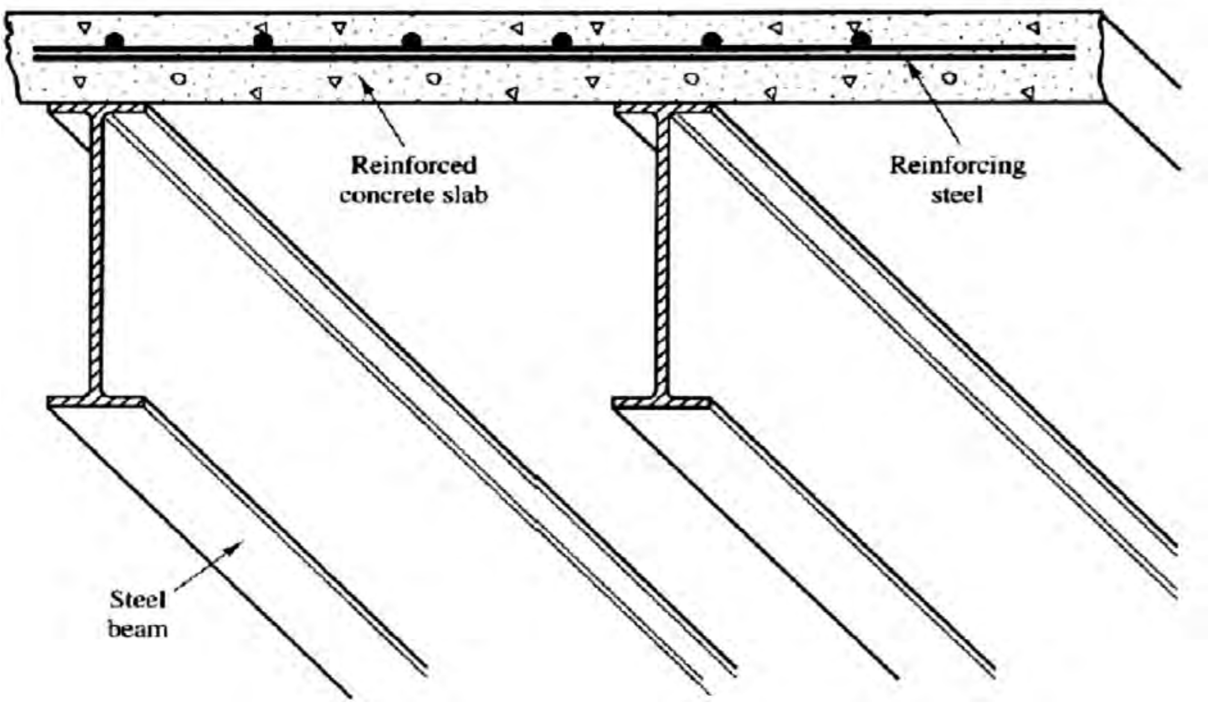


Figure 7.9 Solid reinforced concrete slab on steel beam.

Increased strain rates tend to increase the possibility of brittle fracture. Structures that are loaded at a fast rate may fail by brittle fracture. Cold working and residual tensile stress (such as those caused by welding) may increase the likelihood of brittle fracture. Welding may also leave notches or flaws in the parent metal, which may promote brittle fracture.

With decrease in temperature, most of the strength properties of structural steel (yield strength, tensile strength, modulus of elasticity, and fatigue strength) increase. But the ductility of the material, or the total elongation before fracture, decreases. Furthermore, there is a temperature below which structural steel, when subjected to tensile loads, may fracture by cleavage with little or no plastic deformation.

Investigations of earthquake damage have revealed that buildings of structural steel have performed excellently and better than any other type of construction in protecting life safety and economic loss. This is due to some physical and mechanical properties of steel:

- Lightweight (compared to similar structures made of reinforced concrete)
- Ductility
- High tensile strength

In addition, damaged steel buildings can be repaired relatively easily. All structures (steel, reinforced concrete, and masonry), rely on steel (structural or reinforcing) to supply the ductility and toughness needed to resist severe earthquakes.

In general, structural steel used in bridges, buildings, and towers must possess adequate tensile strength, high ductility, excellent toughness, and sufficient elasticity.

Weldability is important for steel used in the majority of building construction. This property deteriorates with increase in carbon content. Structural carbon steel (A36) has good ductility and is weldable. In fact all ASTM grades of structural steel are weldable. Their carbon content is limited to about 0.25%. **In** steel structures exposed to severe environment, corrosion resistance is required.

7.5 REINFORCING STEEL

Concrete, the most commonly used construction material all over the world, has low tensile strength and modulus of rupture. But it has superior compressive strength. To use this material in applications where it is subjected to tensile or bending forces, it is necessary to improve the tensile strength or bending capacity of structural members. Use of steel reinforcement in a concrete member increases its bending capacity and tensile resistance greatly. In addition, the composite material made with steel and concrete possesses sufficient ductility and improved cracking characteristics.

Reinforced concrete thus behaves as a composite material made from two distinctly different materials: steel and concrete. For reinforced concrete to perform according to theory, it is essential that the steel remains perfectly bonded to concrete. Bonding is achieved by using bars with surface deformations, or deformed bars. Bond capacity in these bars is primarily from surface friction and roughness.

Reinforcing steel is manufactured in three forms:

- Plain bars
- Deformed bars
- Plain and deformed wire fabrics

Deformed bar is a bar that is intended for use as reinforcement in reinforced concrete construction. The surface of the bar has lugs (or *protrusions, deformations)* that inhibit longitudinal movement of the bar relative to the concrete surrounding it (slip). Deformed bars are used in a variety of reinforced concrete construction: slabs, beams, columns, walls, footings, and so on (Fig. 7.10). They are also used in reinforced masonry construction. A plain bar is a round steel bar without surface deformations, and a wire fabric is a flat sheet in which wires pass each other at right angles and one set of elements is parallel to the fabric ax.is. Welded wire fabric is used in floor slabs, roof slabs, slabs on grade, and pipes (Fig. 7.11).

The *nominal dimension* of a deformed bar is equivalent to that of a plain round bar having the same weight per foot as the deformed bar. *Bar numbers* are based on the number of eighths of an inch included in the nominal diameter of the bar. For example, No. 3 bar has a nominal diameter of¾ in. or 0.375 in., No. 18 bar has a nominal diameter of ^{13}¾or 2.26 in., and No. 3 to No. 11 bars are available in all grades. The maximum average spacing of deformations is equal to seven-tenths of the nominal diameter. Thus No. 3 bar has an average spacing of 0.262 in., and No. 18 bar has a spacing of 1.58 in.

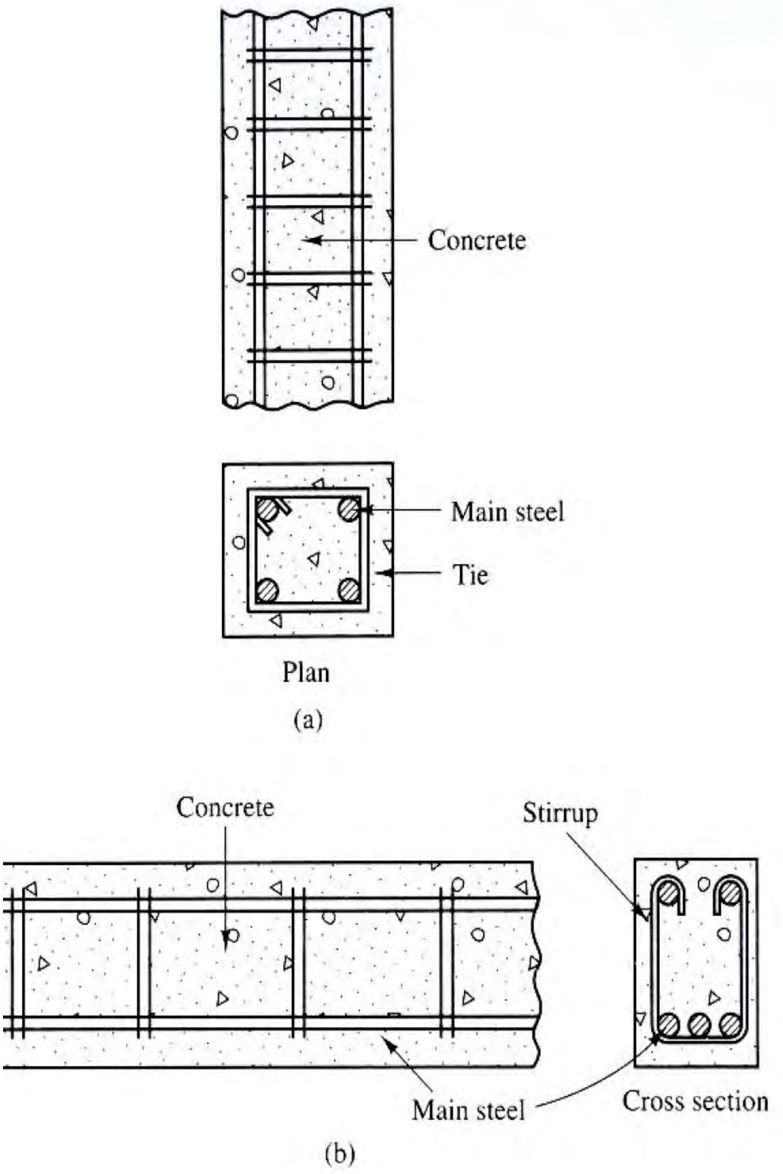


Figure 7.10 Use of reinforcing steel in concrete column (a) and beam (b).

Reinforcing steel is manufactured in four principal *yield levels:*

- 40 ksi
- 50 ksi
- 60 ksi
- 75 ksi

These are designated as grade 40, grade 50, grade 60, and grade 75. Mechanical properties of various grades are shown in Table 7.3. Yield point is the stress corresponding to an increase in deformation at constant load. When the steel does not have a well-defined yield point, yield strength is the stress corresponding to a strain of 0.005 in./in. (0.5% extension) for grades 40, 50, and 60, and a strain of 0.0035 in./in. (0.35% extension) for grade 75 of A615, A616, and A617 steels. For A706 steel, grade point is determined at a strain of 0.0035 in/in.

TABLE 7.3 TYPES AND PROPERTIES OF REINFORCING BARS[8]

ASTM designation	Type	Grade	Tensile strength min. [ksi (MPa)]	Yield strength min. [ksi (MPa))	Size availability (No.)
A615	Billet steel	40	70 (483)	40 (276)	3-6
	bars (plain	60	90 (620)	60 (414)	3-18
	and deformed)	75	100 (689)	75(517)	11-18
A616	Rail steel	50	80 (552)	50 (345)	3-1I
	(plain and	60	90 (620)	60 (474)	3-LJ
	deformed)				
A6l7	Axle steel	40	70 (483)	40 (276)	3-11
	(plain and	60	90 (620)	60 (414)	3-11
	defonned)				
A706	Low-alloy steel deformed bars	60	80 (552)	60-78 (414-538)	3-18

aRange of sizes: No. 3, 4, 5, 6, 7, 8, 9, IO, 11, 14, and 18.

The types of reinForcing bars used in the United States are:

- Billet steel (A615)
- Rail steel(A616)
- Axle steel (A617)
- Low-alloy steel (A706)

Billet steel bars conforming to ASTM A6I5 specifications are the most widely used type. Low-alloy steel bars conforming to ASTM A706 are the most recent type of reinforcement.

Weldability is accomplished in A706 bars by imposing two limits on chemical composition: one on individual chemical elements and the other on carbon equivalent (C.E.). The carbon equivalent is a measure of the chemical elements affecting the weldability of the material (ASTM A706).

$$C\,E. = \%C + \frac{\%\,Mn}{6} + \frac{\%\,Cu}{40} + \frac{\%\,Ni}{20} + \frac{\%\,Cr}{10}\ \frac{\%\,Mo}{50}\ \frac{\%\,V}{10}$$

where C is carbon, Mn is manganese, Cu is copper, Ni is nickel, Cr is chromium, Mo is molybdenum, and V is vanadium. The carbon equivalent limit is 0.55%. In addition, there is a maximum limit of 0.3% and 1.5% for carbon and manganese, respectively. But it should be noted that weldable bars are not really required for reinforced concrete construction, due to increased use of proprietary mechanical connections for butt splicing the rebars.

Bars can be furnished in coils. Coil stock is preferred for use with automatic stirrup and tie bending machines. Coiled stocks are also used by manufacturers of reinforced

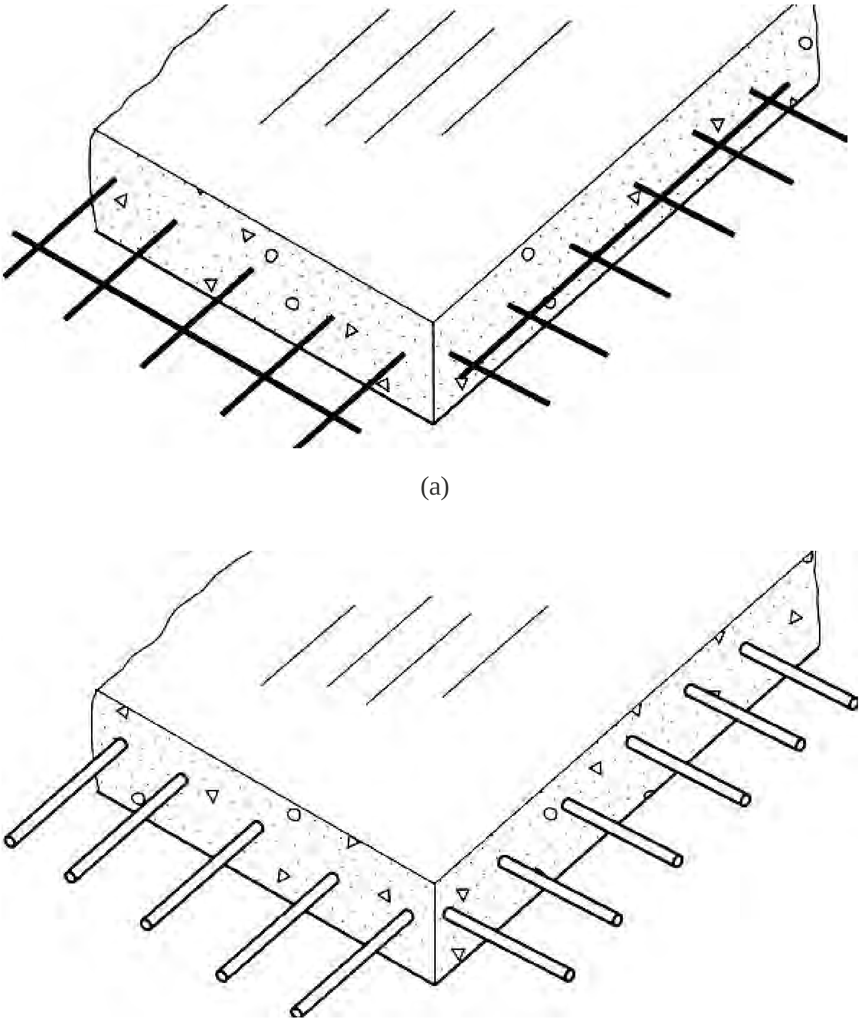


Figure 7.11 Use of (a) welded wire fabric and (b) reinforcing bars in ground-supported slab.

concrete pipes. Rebar manufacturers produce steel in units called *heats.* A heat of steel, depending on the mill, may range from 30 to 200 tons.

7.5.1 Handling

Bars are supplied in bundles, secured by wires or bands, each bundle containing bars of only one size, length, and grade. The bundles are limited to weights that can be conveniently handled with common equipment, approximately 3000 lb (1360 kg) To identify bars, each bundle has a tag made of rope fiber or metal which identifies the order details (name, number, etc.), and size, length, and grade of bars.

Considerable savings in cost can be realized if the bundles can be hoisted directly from the truck to the area on the project site where the bars are to be placed. When the bundles are unloaded in a storage area, the location should provide easy access by truck and for rehandling of the bars. During storage, lumber pieces must be placed under the bars to keep them free from mud and water. Note that the surface condition of bars affect the bond characteristics. The presence of scale, rust, oil, and mud may lower the bond strength severely.

The *scale* occurs at the time the bars are rolled and results from cooling of the hot metal. Loose scale should be removed before placement. Rust increases the normal roughness of the surface and thus improves the bond. But when the rust affects the height of deformation or the weight of the bar, it is harmful. Generally, bars with normal mill scale, rust, or a combination are accepted without cleaning or brushing. Mud coating on the bars should be washed off. Oil or grease should be removed with a torch or by wiping with solvents before placing concrete.

7.6 WELDED WIRE FABRIC

Welded wire fabric is a prefabricated reinforcing material and is available in rolls or sheets. The common types of fabric are shown in Table 7.4. The rolls are of width 5 to 7 ft (1.5 to 2.1 m) and length 150 or 200 ft (45 to 60 m). The sheets come in width of 5 to 10 ft (1.5 to 3 m) and length of 10 to 20 ft (3 to 6 m). They are produced to satisfy the ASTM standards shown in Table 7.5.

There are two types of wire:

- Plain wire
- Deformed wire

Wires are identified by a system that identifies the type of wire and its cross-sectional area. The letter W indicates smooth wire; the letter D shows deformed wire. These letters are followed by a number that represents the cross-sectional area of the wire in hundredth of a square inch. For example, a W4.0 or 04.0 wire has a cross-sectional area of 0.04 in^2.

Plain wire fabrics develop the anchorage (in concrete) at the welded intersection. In deformed wire fabrics, anchorage is developed through the deformations and at the welded intersections.

TABLE 7.4 SPECIFICATIONS FOR WIRE AND WELDED WIRE FABRIC

ASTM designation	Type	Yield strength[a] [(ksi (MPa)l	Tensile strength [(ksi (MPa),l	Size range
A82	Cold-drawn steel wire (plain)	65 (450)	75 (515)	W 0.5-W 31
Al85	Welded steel wire fabric (plain) using A82 wires	65 (450)	75(515)	
A496	Deformed steel wire	70 (485)	80 (550)	D-I-D-31
A497	Welded deformed steel wire fabric using A496 wires	70 (485)	80 (550)	

[a] Yield strength is determined at an extension of 0.005 in./in. of gage length.

TABLE 7.5 PROPERTIES OF WELDED WIRE FABRICS

Designation	Nominal diameter (in.)	Area of wire ($in.^2$)	Area ($in.^2$/ft) Longitudinal	Area ($in.^2$/ft) Transverse	Weight (lb/100 ft^2)
6 X 6-Wl.4 X Wl.4	0.135	0.014	0.028	0.028	21
6 X 6-W2.0 X W2.0	0.159	0.02	0.04	0.04	29
6 X 6-W2.9 X W2.9	0.192	0.029	0.058	0.058	42
6 X 6-W4.0 X W4.0	0.225	0.04	0.08	0.08	58
4 X 4-Wl.4 X WI.4	0.135	0.014	0.042	0.042	31
4 X 4-W2.0 X W2.0	0.159	0.02	0.06	0.06	43

Welded wire fabric is designated by two numbers and two letter-number combination. An example is 6 x 8-W2.9 x W2.9. The first number (6) gives the spacing in inches of the longitudinal wires (Fig. 7.12). The second number (8) is the spacing in inches of

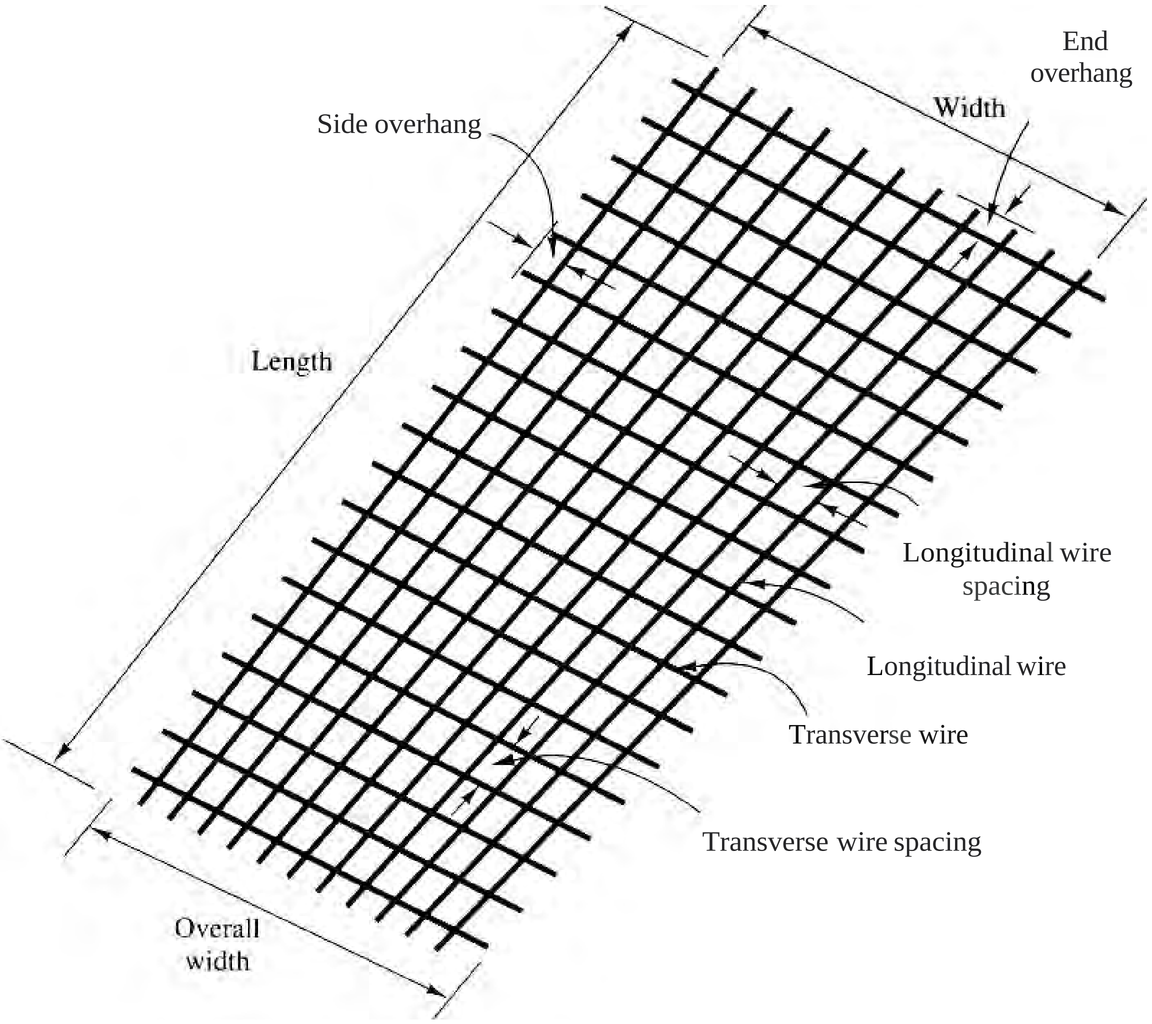


Figure 7.12 Welded wire fabric.

the transverse wires. The first letter of the letter-number combination (W) shows the type of longitudinal wire (plain wire), and the second letter (W) shows the type of transverse wire (plain wire). The first number in the combination (2.9) gives the area of longitudinal wire in hundredths of a square inch, and the second number (2.9) represents the area of transverse wire in hundredths of a square inch.

The longitudinal wire spacing varies from 2 to 12 in. (5 to 30 cm). Spacings of 4, 6, 8, 9, and 12 in. are common in building construction. Transverse wire spacing is normally 4, 6, 8, 12, or 16 in.

Welded wire fabric is used as concrete reinforcement for crack control in residential slabs, driveways, sidewalks, and slabs for light construction. In a slab on grade (or ground-supported concrete slab), cracking is due primarily to three causes:

- Drying shrinkage
- Change in temperature and moisture
- Weak subgrade or soil

When the slab cracks, the surface (within the crack) becomes jagged. If the width of the crack is sufficiently small [less than about ½6 in. (1.5 mm)], the jagged faces are interlocked, which helps to transfer the loads. This mechanism is called aggregate interlock. But as the crack becomes wider, the interlock decreases.

When properly positioned within the cross section of slab, welded wire fabric acts to control the crack by keeping the cracked section of the slab closely knit together. This will allow for effective transfer of the load (through the crack) and also makes the crack less noticeable. Smaller cracks minimize the movement of water through the slab. The use of reinforcement in a slab also reduces the number of cracks.

For proper crack control, welded wire fabric (or similar reinforcement) should be placed in the middle one-third of slabs 4 to 6 in. (10 to 15 cm) thick [or about 2 in. (5 cm) below the top surface]. Some authorities recommend placing the steel at one-third depth from the top of the slab.

The primary objective of placing reinforcement in slab on grade is crack control. In plain concrete slabs, crack control is accomplished by placing control joints at a spacing of less than 15 ft. (4.5 m). When these slabs are reinforced with wire fabric, the control joints can be farther apart.

The most common types of fabric used are 6 x 6-Wl .4x WI.4(10gage) and 6 x 6-W2.9 x W2.9 (6 gage). The most common methods of placing welded wire fabric are (1) by using chairs (or concrete blocks), and (2) by placing concrete in two layers and placing the reinforcement on the first layer. The chairs are supports for steel reinforcement, made of steel or plastic. The spacing of chairs or blocks depends on the reinforcement size and spacing; the common practice is to place them 2 to 3 ft (0.6 to 0.9 m) apart. When concrete is placed in two layers, the first course is generally to middepth (or, slightly more). The reinforcement is then spread on this layer. The top layer of concrete is placed before the lower layer starts to harden.

7.7 TESTING

The following procedure describes the test to determine the tensile properties of steel using round specimens.

Test STL-1: Tension Test of Steel

Purpose: To draw the stress-strain diagram of steel, and determine yield, tensile strength, and percent elongation.

Related standards: ASTM A370, E8.

Definitions:

- *Yield point* is the first stress at which an increase in strain occurs without an increase in stress.
- *Yield strength* is the stress at which the material exhibits a specified limiting deviation from the proportionality of stress to strain.

Equipment: Tension testing machine, wedge grips, micrometer, extensometer.

Sample: Standard 0.5-in. (12.5-mm) round tension test sample with 2-in. (5-cm) gage length.

Procedure:

1. Measure the diameter at the center of the gage length to the nearest 0.001 in. (0.025 mm).
2. Mark the gage length with ink. Gage points should be approximately equidistant from the center of the length of the reduced section.
3. Grip the specimen at sections outside the gage length.
4. Apply the load at a constant rate.
5. Measure extensions at predetermined load intervals.
6. When the increase in load stops or hesitates, record this load. The corresponding stress is the yield point.
7. When no yielding is noticed, determine yield strength using the offset method (0.2% offset) or percent extension method from the stress-strain diagram.
8. Plot the stress-strain diagram.
9. Calculate the tensile strength by dividing the maximum load during the test by the original cross-sectional area.
10. Calculate the elongation over the gage length and percent increase.

Report: Report the tensile strength, yield strength (or point) and the method of determination, and percent elongation.

CHAPTER 8

Other Materials

The most common civil engineering materials were described in previous chapters. Concrete, steel, wood (and wood products), masonry, and asphalt comprise the majority of structural materials. A few other materials that are important to civil and construction engineers are discussed in this chapter.

8.1 PLASTICS

The name *plastics* is used to describe any of a group of synthetic or natural organic materials that can be shaped when soft and then hardened. The basic component of organic plastics is a resin that can flow when softened. Although the resin used in the manufacture of a plastic product can be synthetic, partially synthetic, or natural, the majority of plastics are made from synthetic chemicals. Note that all three types of resins are organic, which means that these chemicals are similar to other organic compounds, such as sugars and dyes. Organic compounds by definition, contain carbon.

The component molecules of resins used in the manufacture of plastics are very large; they are made up of relatively simple repeating units. A repeating unit, called mer, may exist in a single unit (called a monomer), in two units (called a dimer), or in many units (called a polymer).

Thus *mer* can be defined as a unit consisting of relatively few hydrocarbon atoms joined to other units to form a polymer. Similarly, *polymer* can be defined as a molecule made up of repeating groups of mers. It may also be described as a large molecule comprised of hundreds or thousands of atoms, formed by a continuous chain of small molecules which are monomers. For example, polyvinyl chloride is a polymer made from a monomer called vinyl chloride. The most common natural polymers are wood and rubber.

The name *polymer* comes from the Greek words *poly,* meaning "many", and *meros* meaning "part." Of the polymer materials (also called macromolecules) in engineering, plastics form the dominant group. Plastics are produced using petroleum or natural gas as raw materials. The process of building up small molecules in a long chain to form a large molecule is called *polymerization.* This is accomplished under heat, heat and pressure, or in the presence of catalysts.

The structure of plastics is similar to that of other petrochemical products or hydrocarbons. *Hydrocarbons* are substances containing only the chemical elements carbon and hydrogen. Note that petroleum and natural gas are complex mixtures of hydrocarbons formed naturally in the earth. Methane, for example, which is the main component of natural gas, is a hydrocarbon. The molecular structure of methane consists of a single carbon forming a single molecular bonding with each of the four hydrogen atoms.

A large number of polymers are hydrocarbons. A synthetic hydrocarbon polymer such as polyethylene is composed of hydrocarbon chains consisting of hundreds or thousands of carbon atoms as compared to a simple molecular structure of methane. Here the word *synthetic,* which commonly means "not genuine" or "artificial" (e.g., synthetic stone, synthetic diamond), is used to describe a product formed by chemical reaction as opposed to that of natural origin.

Polymers, in the form of plastics, rubbers, and fibers have played important roles in everyday life. They are used in thousands and thousands of products, ranging from window curtains and computer hardware to water pipes and entry doors. In fact, it is nearly impossible to live without the help of this human-made material, which we learned to make during the second half of the nineteenth century.

8.1.1 Types of Plastics

Plastics (or polymer resins) fall into two classifications:

- Thermoplastics
- Thermosets

A *thermoplastic* material is a polymer material that softens and melts gradually when heated and can be reshaped when still warm. Thermoplastics have linear molecular chains (without cross-linkage) which move in relation to one another when heated or cooled. The most common thermoplastics are polyethylene, polypropylene, polystyrene, and polyvinyl chloride (Table 8.1). The majority of plastics of today are thermoplastics. Polyethylene and polyvinyl chloride comprise nearly 50% of the total plastic production in the United States.

A *thermosetting* material is a polymer material that cannot be reshaped after the manufacture. The molecular structure of thermosets is similar to that of thermoplastics before molding. But during the hardening process these chains are cross-linked to form

TABLE 8.1 COMMON PLASTICS

Thermoplastics	Thermosets
Polyethylene	Epoxide (Epoxy)
Polyvinyl Chloride **(PVC)**	Phenol-formaldehyde
Polypropylene	Melamine-formaldehyde (phenolic)
Polystyrene	Unsaturated polyester
Polyamide (nylon)	Polyurethane
Polymethyl methacrylate (Acrylic)	

an interconnected network of chains that are not free to move. The most popular thermosets are unsaturated polyester, epoxides, phenol-formaldehyde, and polyurethane.

Thermoplastic resins do not undergo permanent change on reheating. They soften and melt when heated, and resolidify upon cooling, like wax or butter. The molded shapes are retained upon cooling. Any object made *with* thermoplastics can be remolded into a new shape. Thermoplastics creep considerably, more than thermosets, particularly at higher temperatures. They are generally isotropic and show consistent properties and thus can be used for light structural applications.

Thermosetting resins first soften on heating, and on continuous heating harden or set to become relatively rigid, like an egg. When reheated, they do not soften and cannot be remolded. When reinforced, they show higher strength and less tendency to creep (compared to thermoplastics) and can be used in light structural applications.

Molecules of both thermoplastic and thermosetting resins are high polymers with long and continuous carbon-atom chains for a molecular framework. But as noted earlier, the setting process of the thermosets binds the molecular chains together, making them larger and still more complex.

Thermoplastic products are manufactured using a number of methods. The most common methods in mass production are extrusion and molding. The machinery for the extrusion process consists of a heated barrel with a screw turning inside it. Resin in the form of granules or powder is fed into the barrel, and upon heating, is forced through the screw in much the same way that toothpaste is squeezed from a tube. The fluid comes out through a die or mold that forms the shape of the extruded plastic. PVC and polyethylene products of indefinite length such as pipes, tubes, rods, and edgings are commonly manufactured using this process.

Thermoplastic products can also be produced by molding. In the injection molding process, the resin granules are fed into a heated barrel. The fluid is then forced through a nozzle at *high* pressure (by a ram) and later led to the cavities of the mold. Cold water circulates in the mold, and when the fluid sets, it takes up the required shape. Thermoplastics such as polyethylene, polystyrene, and nylon are suitable for injection molding.

Thermosetting products are generally made by a combination of compression molding, transfer molding or injection molding. In the compression molding, the shaping of the plastic is accomplished by the application of heat and pressure in a suitable mold. This method can be used for both thermoplastics and thermosets, but is best for the latter.

The mold is opened and a charge is placed in it which is then closed and heated. The hot viscous mass flows into all parts of the mold as the pressure is applied. The mold remains closed until the part is fully formed. A thermoplastic softens, flows, fills the part of the mold, and remains soft until the mold is cooled. A thermosetting material first softens and then hardens or cures to a solid infusible mass. It may then be ejected from the mold while hot, whereas the thermoplastic material requires that the mold be cooled before the part can be removed. The injection molding method is similar to that of thermoplastics. In the transfer molding method the thermosetting powder is put in the bottom half of a heated mold. As the material melts and begins to set, the upper half of the mold drops and forms it into desired shape under both heat and pressure.

Light cross-linking of certain linear polymers produces an additional class of plastics: rubberlike materials called *elastomers* (also called *synthetic rubbers).* This material has a high level of elasticity (the capacity to recover large deformations) and is simiJar to natural rubber.

The effect of the length of application of elevated temperature on thermoplastics and thermosets is illustrated in Fig. 8.1. Continuous heating increases the softening point of thermosets and makes them hard. But it should be noted that some plastic materials show characteristics of both thermoplastics and thermosets.

8.1.2 Properties of Plastics

The mechanical properties of plastics are affected by:

- Rate of loading
- Temperature
- Environmental conditions

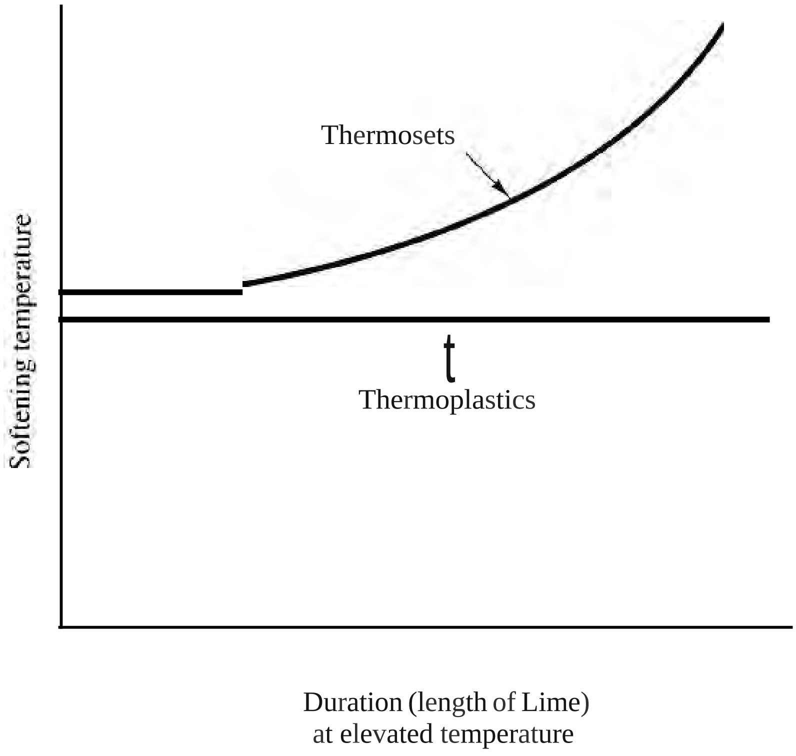


Figure 8.1 Effect of length of time at elevated temperature on plastics.

The behavior of plastics can be described as partly elastic and partly viscous. This viscoelastic behavior is both temperature and time dependent. Plastics that are hard and strong at ordinary temperatures may be weak and soft at higher temperatures. Some plastics which are strong and tough under compressive loads (such as polystyrene) may be brittle under tensile loads (Fig. 8.2).

It should be noted that the mechanical properties are not the same for all varieties of plastics. They depend on the length and shape of the molecules of individual polymers. Typical stress-strain curves of thermoplastics and thermosets are shown in Fig. 8.3. Most plastics exhibit limited elastic range and a low modulus of elasticity. Some plastics are brittle and weak; others are relatively strong and flexible. In the latter type of plastics, after the occurrence of necking down or yielding, elongation continues for about 100 to 200% strain (percent elongation).

For most plastics, the modulus of elasticity in tension is not the same as in compression and is generally less than 1 x 10^6 psi (6.89 GPa). This low modulus of elasticity gives rise to unsafe deformations and deflections when plastics are used in structural or load-bearing applications. Some of the properties of selected thermoplastics and thermosets are listed in Table 8.2 and discussed briefly in the following paragraphs.

Polystyrene is one of the commonest thermoplastics. This resin was discovered in 1831, but industrial production did not start until 1930. Polystyrene has a specific gravity of 1.05 and its tensile strength is low, generally less than 7000 psi (48.5 MPa), and its modulus of elasticity is also low. It has good water resistance and dimensional stability and is inexpensive. But it possesses poor heat resistance and limited weather resistance. Moreover, polystyrene is brittle and lacks toughness.

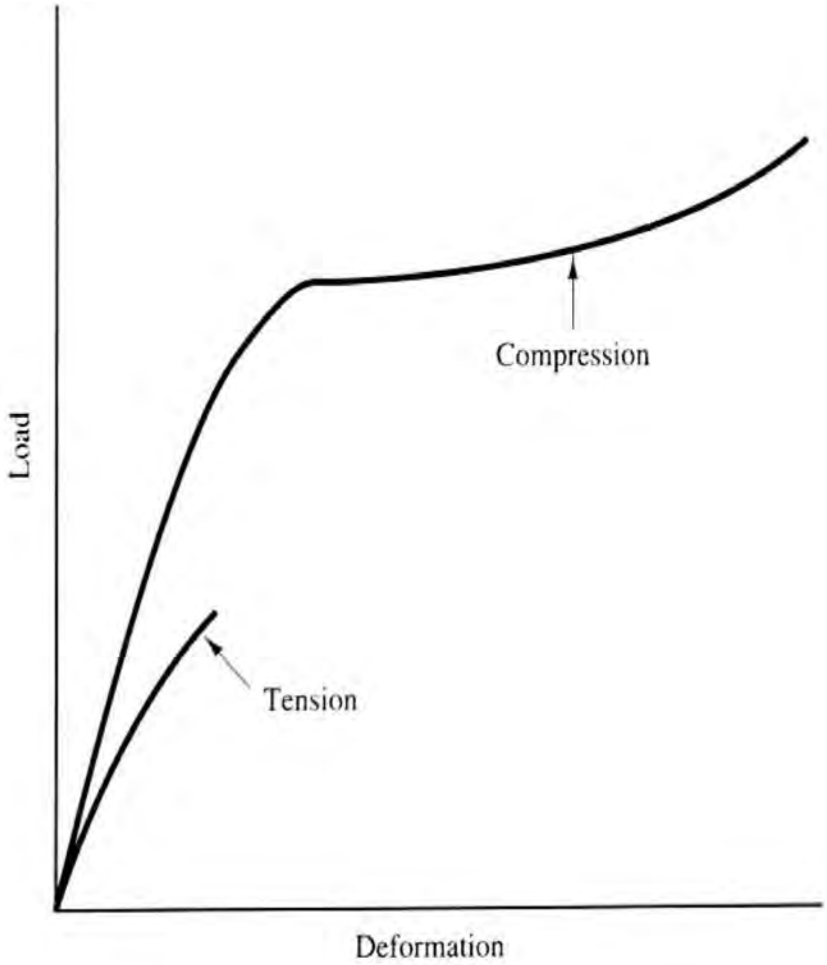


Figure 8.2 Load–deformation diagrams of polystyrene.

TABLE 8.2 PROPERTIES OF SELECTED PLASTIC

Material	Type	Specific gravity	Tensile strength [ksi (MPa)]	Modulus of elasticity [ksi (GPa)]	Compressive strength **[ksi (MPa))**	Coefficient of expansion [per °F x $10^{\cdot 6}$ (per °C x $J0^{\cdot 6}$)]
Polyethylene	Thermoplastic	0.92	1.8-4.0 (12.4-27.5)	19-160 (0.13-1.1)	0.4-2.4 (2.8-16.5)	100--120 (180-215)
PVC	Thermoplastic	1.3-1.4	I l.5-8.0 (10.3-55.2)	1-800 (0.007-5.5)	0.1-13 (0.7-89.6)	30 (54)
Polypropylene	Thermoplastic	0.91	4.0-5.5 (27.6-40)	120-175 (0.8-1.2)	8.5-10 (58.6-69)	170 (308)
Polystyrene	Thermoplastic	1.05	4.0-7.0 (27.6-27.5)	20-50 (1.4-3.5)	1.3 (7.l)	38 (68.5)
Nylon	Thermoplastic	1.14	7-12 (48.3-82.8)	260-410 (1.8-2.8)	7-13. (48.3-89.6)	55 (90)
Unsaturated polyester	Thermoset	1.6-2.2	4 (27.6)	300--1500 (2.1-10.31)	20.-25. (138-173)	42 (75)
Phenol-formaldehyde	Thermoset	1.3-1.9	4-8 (27.6-55.2)	1000-1500 (6.9-10.3)	20-25 (138-172)	45 (81)
Polyurethane	Thermoset	1.2	5 (34.5)			32 (58)
Acrylic	Thermoplastic	1.19	8-10 (55.2-68.9)	420 (2.9)		40 (72)

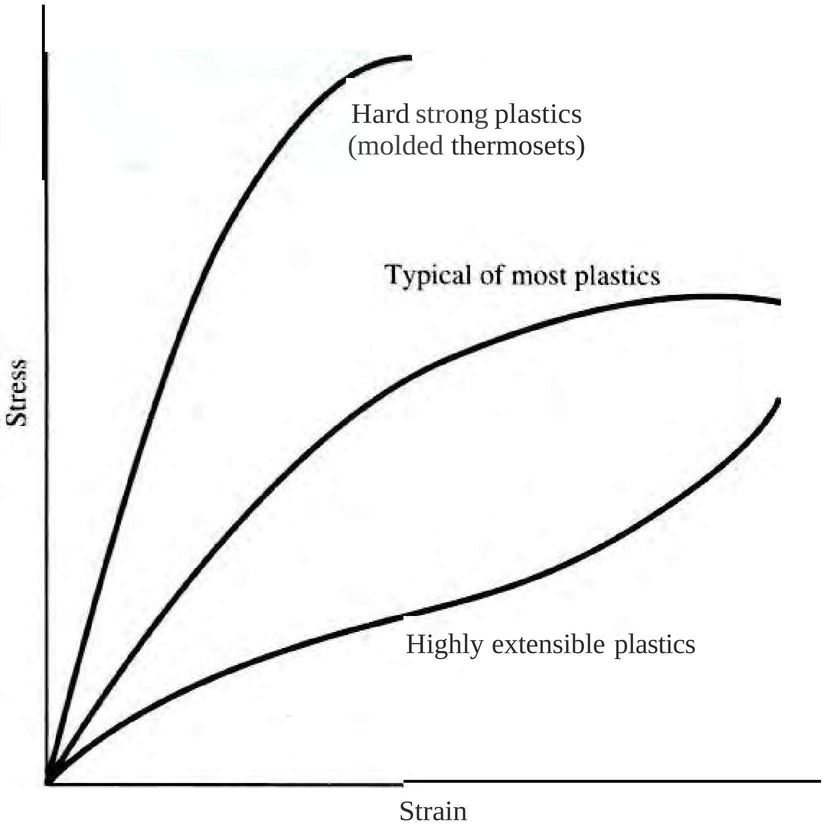


Figure 8.3 Typical load-deformation diagrams of plastics.

Pure polystyrene, which is crystal clear, is used for storage containers and cups. Polystyrene and expanded polystyrene (made by heating it with a foaming agent) is used in tiles, packaging, containers, foams, and housewares. Foamed polystyrene panels are used in poured-in-place concrete wall systems and as insulation boards for foundation walls, masonry and wood walls, and roofing.

Polyvinyl chloride (PVC) is a commonly used thermoplastic material with a specific gravity of about 1.39. The industrial production of PVC began in Germany around 1925. It is made from a monomer, vinyl chloride. Its modulus of elasticity is about 0.5×10^6 psi (3.6 0Pa). The tensile strength of PVC is nearly the same as that of polystyrene. Its coefficient of thermal expansion is less than 0.3×10^{-4} per °F. PVC is also an excellent insulator. Common applications of PVC are in raincoats and shower curtains. It is used extensively in floor tiles, electric cables, flexible sheeting, hoses, pipes, luggage, moldings, expansion joint fillers, decorative wall coverings, and other products.

Polyethylene is also a common thermoplastic with a specific gravity of about 0.92. It is a tough, weather-resisting plastic and is durable. The resistance to moisture of polyethylene is very good. In addition, polyethylene has excellent electrical properties and favorable chemical resistance. Its tensile strength is very low, generally less than 2000 psi (13.8 MPa). Its modulus of elasticity is also very low, and does not exceed 0.16×10^6 psi (1.1 GPa). The standard value of modulus of polyethylene is 0.019×10^6 psi (0.13 0Pa). Its coefficient of linear expansion is 1×10^{-4} per °F. The common application of polyethylene is as polyethylene bags. It is used in the manufacture of films, sheets (clear or opaque), moldings, piping's, electrical conduits, tanks, foams, and bottles. Polyethylene films and sheets are used as dampproof course, membrane, and curing membrane.

Polypropylene is another thermoplastic that has a low specific gravity (same as polyethylene) and low modulus of elasticity. In fact, polypropylene is the lightest of all thermoplastics. Its coefficient of thermal expansion is comparable to that of polyethelene, but it has a higher softening point and is shinier. It bas good heat resistance but degrades under sunlight. Thanks to good abrasion resistance and hardness, polypropylene is used for pipe, moldings, sheets, geomembranes and so on.

Acrylics are thermoplastic materials, which are crystal clear in natural form but are commonly manufactured in a wide range of colors and shades. They exhibit good weathering resistance and ease of forming. Their tensile strength, compared to other thermoplastics, is relatively high, about 10,000 psi (69 **MPa),** but their modulus of elasticity is comparable with that of others. They are used in light fittings, skylights, screen doors, and so on. They are also used in paints and adhesives.

Polyester is a thermosetting resin that has a specific gravity ranging between 1.6 and 2.2. Its modulus of elasticity is fairly low, generally around 0.3×10^6 psi (2 GPa). But glass-reinforced polyester has higher modulus, as much as 2×10^6 psi (13.8 GPa). Its coefficient of thermal expansion is about 0.4×10^{-4} per °F. Polyester is used in the manufacture of fiberglass products and composite materials.

Phenol-formaldehyde is a common thermosetting resin with a high specific gravity (1.9). Its tensile strength varies between 4000 and 8000 psi (27.5 and 55 MPa). Its coefficient of linear expansion is one of the lowest among plastics. As a molded material, this plastic (also called Bakelite) is used in the manufacture of lavatory seats, electrical fittings and equipment, and decorative laminates.

General properties. Plastics are dimensionally unstable materials. Dimensional stability of a material depends on its stiffness or elastic modulus. Plastics are less elastic than steel or concrete. They are subject to creep, which is the increase in deformation, under load, with time. The rate of creep in plastics is much higher than the rate in concrete. The creep deformation increases with the stress level. Because of this, the modulus of elasticity of plastics decreases with the increase in load and its duration. As a result, plastics become dimensionally unstable under load. But it should be noted that most plastics are dimensionally unstable not only because of creep but also because of the tendency to shrink. Thermosetting plastics shrink appreciably in comparison to thermoplastics.

Generally, plastics do not transmit vibrations very well. They tend to absorb part of the vibrational energy, which is called damping capacity. The high damping capacity of plastics make them suitable in applications where vibration is encountered.

Plastics retain their color in indoor applications. In outdoor applications, however, color fastness depends on weather conditions. Ultraviolet radiation in sunlight is a significant factor in the weathering of plastics. Weathering can take several forms: fading, yellowing, and roughening of the surface. Temperature (heat) and humidity changes (moisture) affect the color and accelerate the aging of plastics.

Carbon in plastics has a tendency to combine with oxygen from the air to form CO_2. This tendency is more pronounced at high temperatures. Thus all plastics have an upper limit on service temperature beyond which they will decompose. Organic compounds in general are partially soluble in similar compounds, a property that also applies to plastics.

Fire resistance is an important property in buildings. Most plastics are flammable; however, there are large differences between various plastics in terms of the flammability. Polyethylene burns readily when fired by a flame and extinguishes itself when the flame is removed. The addition of fire-resistant materials in plastics may not provide a permanent resistance. Moreover, some plastics may give out heavy toxic smoke in a fire. These kinds of plastics should not be used in exit areas in buildings, such as around stairways and corridors.

Most plastics have low water-absorption properties. They are particularly suitable as impervious membrane layers to prevent the movement of water. Examples of these applications are in foundations and in storage, sanitary and water supply installations. In applications requiring permanent or temporary solution to water movement (such as in foundation slabs and for concrete curing), plastics is an ideal choice.

The coefficient of thermal expansion of plastics is higher than that of other materials, and is 5 to 10 times that of steel or concrete. This means that allowance should be made (such as providing construction joints, slotted holes, etc.) in plastics construction for thermal expansion and contraction of the member.

The thermal insulation property of most plastics is superior to that of most other materials. A 1-in. (2.5-cm) polyurethane foam provides as much thermal insulation as that of 20 in. (50 cm) of clay brick. Polyurethane foam and expanded polystyrene are commonly used as thermal insulation material in sandwich construction and in buildings. But note that the acoustical insulation of plastics is poor. This means that improvement in energy consumption may be offset by poor sound or noise protection.

Poisson's ratio is a measure of the reduction in the cross section that accompanies the elongation. For most brittle plastic materials, Poisson's ratio is around 0.3. For flexible plastics, its value is close to 0.4.

Modified plastics. Many plastics have their basic properties modified by the addition of substances such as plasticizers, antioxidants, fillers, and colorants (pigments). Plasticizers are added to soften plastic and make it easier for shaping. Antioxidants prevent degradation by light and heat, fillers provide toughness and strength, and colorants give color to plastics. Fibers are the most common type of fillers added to change the mechanical properties of plastics.

Thermosetting and thermoplastic resins can be reinforced to improve their properties. A wide range of materials can be employed as reinforcements or fillers. They include glass, asbestos, jute, and mineral fibers or fillers. For high-strength applications, graphite (carbon), aramid (Kevlar), glass, and boron fibers can be used, in which case the plastics are called *reinforced plastics.*

In addition to increasing the stiffness and strength, the use of fibers may reduce shrinkage, improve abrasion resistance, increase toughness, and provide dimensional stability to plastics. Note that tensile strength of glass fibers can range between 250 and 350 ksi (1720 and 24 IO MPa), and that of graphite or carbon fibers may be as high as 500 ksi (3450 MPa). These high-strength fibers also have a high modulus, and their use in plastics imparts sufficient stiffness and strength to the material.

As they are relatively inexpensive and possess desired properties, glass fibers, are the most widely used reinforcement in plastics. They are primarily silica (SiO_2) and are manufactured by extruding molten glass at a high velocity through a large number of holes in a platinum plate. Glass fiber is resistant to high temperature, transparent (does not change the color of the plastic), and isotropic. Carbon fiber is lighter than glass fiber. It has higher tensile strength and modulus of elasticity. Other advantages of carbon fiber is that it is chemically inert, dimensionally stable and has high electrical and thermal conductivity along the fiber axis. But it is black in color and will change the color of the plastic. Both glass and carbon fibers are used with thermoplastics and thermosets such as epoxy resins, polyester, and polypropylene in the manufacture of products such as boat, tennis racquet, tanks, pipes, and benches.

In summary, most plastics have low strength and very low modulus. Due to this inherent weakness, plastics are not employed in load-bearing construction. But they are good electrical and thermal insulators. The principal advantages of plastics lie in their low specific gravity, moldability, aesthetic qualities, simplicity in fabrication, adaptability, and low cost. But the biggest disadvantages are that plastics are difficult to repair, have high thermal expansion potential, creep considerably, and possess extremely low fire resistance.

8.1.3 Uses of Plastics

Plastics have revolutionized a number of industries, such as automobile, electrical, and electronic. Lower prices have contributed to the universal application of plastics. Polyethylene, polypropylene, polystyrene, and PVC represent over 85% of world plastics consumption. In civil engineering applications, plastics possess a number of advantages. The most important ones are:

- Plastics have a favorable strength/weight ratio.
- Because of its lightness, plastics present ease in handling, transportation, storage, and assembly.
- Plastics can be molded to any shape and pattern.
- Most plastics are generally maintenance free and have good corrosion resistance.
- Plastic products come in variety of colors and textures.
- Plastics can be manufactured with consistent quality. They are easy to manufacture into components.
- Plastics are very economical.

Based on these advantages, it can be said that plastics are very suitable in the manufacture of prefabricated components for both indoor and outdoor applications. Moldings, floor and wall coverings, windows, skylights, and countertops exemplify some of the common uses of plastics. Success in the use of plastics depends on several factors, such as fire resistance requirements, thermal and acoustical needs, dimensional stability, and weathering tolerances.

Dimensional-stability problems of plastics were discussed earlier. To attain sufficient dimensional stability in civil engineering structures, large components of plastics are needed in load-bearing construction. This may prove uneconomical and impractical. Because of low stiffness and strength, plastics are not generally used for load-bearing construction.

However, a new type of reinforcement using fiber-reinforced rods is being tried for concrete. Aramid fiber-reinforced rods have been used for a prestressed concrete berth in Japan. A 210-ft (64-m)-cable-stayed bridge has been built in Scotland in which the deck and tower are constructed from interlocking cellular glass-reinforced plastic protrusions that are glued together. Composite plastic and steel piles have been used to help solve problems of durability and corrosion in marine environment. Steel pipes encased in recycled plastics are found to be immune to attack by marine borers, which destroy timber piles.

Manufactured plastics have good surface finish and may not require maintenance. Because of this and due to their availability in a large range of colors and textures, plastics are commonly employed for floor and wall tiles and countertops.

The excellent water resistance property of plastics was discussed earlier. Polyethylene, PVC, and a few other plastics are used extensively as dampproof membrane (plastic sheet) to prevent the rise of moisture from soil through a concrete floor. Plasticized PVC waterbars are used in construction and expansion joints. Plastics are commonly used as a dampproof course or dampproof layer in brick and block wall construction.

With very good thermal characteristics, plastics are the most popular thermal insulation material. Polyurethane, polystyrene, and vinyl resins are used extensively as wall and ceiling insulation material in both cast-in-place (as foamed insulation) and precast constructions (as rigid insulation).

Summarizing, plastics can be used in applications that demand moisture prevention, thermal insulation, lightness, electrical resistance, passage of light, good wearing surface, and moldability. However, the most important factor in the universal adaptation of polymer materials is that they are relatively inexpensive.

8.2 SOIL

The earth's crust, which is 6 to 9 miles (9.6 to 14.4 km) thick, is made up of rocks and unconsolidated sediments or overburden termed *soil.* (Fig. 8.4). Soil is the natural product of weathering and mechanical disintegration of rocks. The process of weathering, which has been going on for millions of years, has several forms: physical, chemical, and organic. Mechanical disintegration occurs during the transportation of rock fragments by water, ice, or wind. In engineering, soil is defined as the unconsolidated material above the bedrock.

The primary function of soil in civil engineering is to support the loads from above. Buildings, bridges, roads, or tanks, no matter what the constructed structure is, all should be supported by the ground. In this role the soil acts as a universal foundation or load-carrying material. Soil also has a secondary role as a construction material-similar to concrete and brick-for walls and dams and for backfill. Mud bricks and soil-cement blocks are used for walls in buildings. Dams can be constructed using compacted soil and/or soil cement.

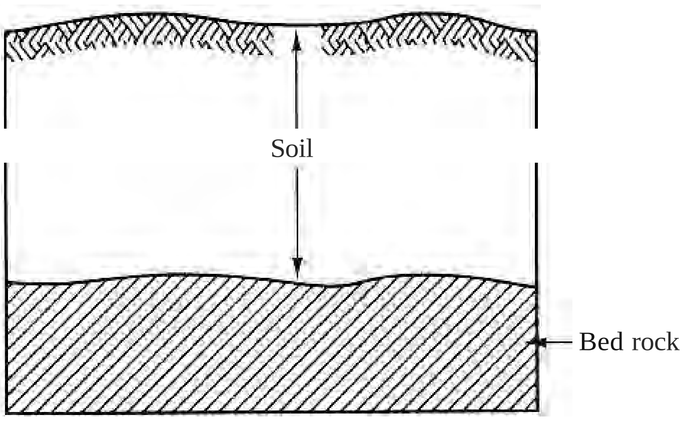


Figure 8.4 Section of the earth's crust.

8.2.1 Types of Rocks

Characteristics of soil depend on the parent rocks from which the soil is derived. Rocks are mixtures of several minerals, and may be one of the following:

- Igneous
- Sedimentary
- Metamorphic

A *mineral* is a naturally occurring chemical element or compound that has a definite crystalline structure and distinctive physical properties. The most common rock minerals are feldspars, quartz, kaolinite, muscovite, and calcite. Feldspars are the most important group of rock-forming minerals and are abundant in the earth's crust.

Igneous rocks are formed by the cooling and hardening of molten magma. About 95% of the earth's crust is made up of igneous rocks. Some of the important igneous rocks are granites, basalts, pumice, scoria and rhyolite. The mineral composition of granite is principally feldspars [potassium aluminum silicate, $K(Al)Si_3O_8$, sodium aluminum silicate, $Na(Al)Si_3O_8$, or calcium aluminum silicate, $Ca(Al)Si_3O_8$] and quartz (silicon dioxide, SiO_2).

Rocks formed by the accumulation or deposit of transported fragments, followed by consolidation, are *sedimentary rocks*. Transportation is by water, ice, and wind. Only about 5% of the earth's crust is made up of sedimentary and metamorphic rocks. Of the exposed rocks, nearly 75% are sedimentary rocks. The more common sedimentary rocks are sandstones, limestones, and shales. Quartz is the most abundant mineral in sedimentary rocks. Limestone contains primarily calcite mineral (calcium carbonate, $CaCO_3$). Shale is formed from the hardening of silts and clays. Sandstone is formed from sand (quartz) under pressure.

Rocks that are formed by alteration or metamorphosis of sedimentary and/or igneous rocks from heat, pressure, or both are called *metamorphic rocks*. Schist, gneiss, slate, and marble are some examples of metamorphic rocks.

8.2.2 Types of Soil

Soil consists of one or more of boulders, gravel particles, sand grains, silt particles, clay deposits, and organic matter. The percentages of these types in any soil vary between deposits.

Gravel and *boulder* are large particles derived from weathering or mechanical disintegration of parent rock. They are similar in mineral composition to the unweathered or parent rock. Quartz is the predominant mineral in many gravels and sands. *Sand* consists of particles that are resistant to weathering of rock. It may include particles of mica, gypsum, and limestone. Boulder, gravel, and sand do not possess the interparticle bonds that exist in clays and silts, and can be excavated with a shovel.

Silt results from grinding action between pieces of rock of different sizes. It can be described as a type of soil intermediate between fine sand and clay. Silt contains mainly powdered quartz and silica. The particles are round and smooth and can easily be molded and crushed with fingers. If you take a sample of moist silt in the palm of your hand and shake it horizontally, the moisture will come to the surface and will recede when pressed. Silt deposits are commonly found in plains and are generally well graded and stable.

Clay deposits consist of clay minerals, which result from chemical weathering or decomposition of minerals of igneous and sedimentary rocks (feldspars and mica) followed by consolidation. The main groups of clay minerals are kaolinite, illite, and smectite. They are principally oxides of silica and aluminum (mostly hydrated aluminum silicates) packed in a manner that shows a platelike structure. Varying amounts of oxides of iron and magnesium, and organic particles left due to decomposition of plants and animals, may also form constituents of clays.

Clay particles stick to the fingers when wet. Squeezed between fingers, wet soft clay exudes out. Clays possess plasticity, especially when wet. *Plasticity* is the property that gives the clayey soil the ability to be remolded and deformed without breaking apart. All clays are plastic. Silts also exhibit plasticity, but to a lesser extent.

Large quantities of silt and clay are found in sedimentary deposits of lakes and near shorelines at river exits. Note that clay particles are the principal source of cohesion in cohesive soils. Even when present in small amounts, clay tends to dominate the soil behavior. The term *loam* is used to describe a loose-textured mixture of sand, clay, and silt. For example, soil containing 60% sand, 10% silt, and 30% clay is called sandy loam.

Organic matter in soils is derived from plant or root growth. Even small amounts of this material may significantly affect the soil compressibility and other properties.

Cohesive and cohesionless soils. Soil is largely divided into two types:

- Cohesive soils
- Cohesionless soils

A *cohesive soil* is any soil whose grains stick together on wetting and subsequent drying so that some force is required to separate them in the dry state (e.g., clay lumps). This type of soil becomes plastic when wet and is very compressible. With a sufficient amount of moisture, a cohesive soil may even act like a viscous fluid. Alterations in the water content of cohesive soils are followed by volume changes in the soil. But it is important to note that any two cohesive soils of apparently the same physical or mineral composition may not possess the same properties.

A *cohesionless soil* is any soil in which the grains fall apart upon drying but sticks together when wet (e.g., one needs wet sand to build a sand castle). The attraction between particles in cohesionless soil is due to *surface tension* forces (called *apparent cohesion)* in the water layer. The water film surrounding the particles pulls the particles and holds them together. The cohesionless soil does not become plastic in any water content and is only slightly compressible. It is more permeable to water movement than is cohesive soil.

Coarse grained and fine grained soils. In the Unified Soil Classification system (USC), soil is classified as *coarse grained* if more than 50% of the sample is retained on a No. 200 sieve (0.074 mm). It is *fine grained* if more than 50% of the sample passes a No. 200 sieve.

Coarse-grained soil is *gravel* if more than half of the coarse fraction is retained on a No. 4 sieve (4.76 mm), and is *sand* if more than half of the coarse fraction is between a No. 4 and a No. 200 sieve. Gravel is further subdivided as clean gravel and gravel with fine, based on the amount of fines. Similarly, sand is divided into two categories: sand with fine and clean sand, depending on the amount of fines. Fine-grained soil is called silts and clays.

8.2.3 Characteristics and Properties of Soils

Soil is a combination of very dissimilar materials in three phases: solid, liquid, and gas. The strength and behavior of soil is a function of the group action of the particles and the interaction of the three phases. Properties of soil in any one phase may be totally different at other phases.

As explained earlier, soil is used either as a foundation material or a construction material. As a foundation material, soil investigations are carried out to determine its characteristics for assessing the load-carrying capacity of the soil, the settlement off oundations, the groundwater movement, and the lateral stability. In the design and construction of highway pavements, bridge piers and abutments, retaining walls, embankments, dams, tunnels, and foundations of structures, these aspects are required. As a construction material, remolded properties of soil are important. Several soil properties that affect its performance as a foundation material and as a construction material are discussed in the following paragraphs. The basic physical properties of soil are:

- Particle-size distribution
- Water content
- Specific gravity
- Void ratio
- Unit weight

Important engineering properties are:

- Permeability
- Compressibility
- Shear strength

Particle size. The particle size of soil (or grain size) is taken as the size of the smallest hole or sieve through which the particles will pass. It represents a nominal diameter of the soil particles.

The soil particles range in size from about ¾ in. (] 0 mm) to 0.0000 I mm or 0.0 I µm. Some particles are visible to the naked eye, some are microscopic, and the balance are submicroscopic in size. Particles of cohesionless soil, typically, are visible to the naked eye, and particles of cohesive soil are microscopic and submicroscopic.

Physical separation of a sample of soil into two or more fractions, each containing only particles of certain sizes, is termed *fractionalization* or *gradation.* Using *mechanical analysis* or *sieve analysis,* we can determine the percentage of particles of various sizes. This is carried out by taking a representative sample of the soil and shaking it through a stack of sieves with openings of known sizes arranged in decreasing size from top to bottom.

The sieve sizes range from 4 in. (101.6 mm) to No. 400 (0.037 mm). The sieve openings are square in shape. The sieve sizes are referred to mesh openings from 4 in. (101.6 mm) to ¼ in. (6.35 mm), and then by numbers. Soil particles of size below No. 200 sieve (0.074 mm) are very fine, and soils with these particles offer resistance to water flow.

The grain-size analysis provides data that help to determine the suitability of a particular soil for a certain construction project, the permeability and the capillary action. Soil *permeability* measures the ease with which a fluid will flow through a soil, and *capillarity* is associated with retention and rise of water above the water table (explained further later in the section on moisture content). Both these properties are connected with gradation.

The sieve analysis yields the gradation of the particles, with which a plot of *grain-size distribution* or *gradation curve* can be established. The horizontal axis of the gradation curve shows the particle sizes, plotted from left to right in increasing magnitude (Fig. 8.5). The ordinates are percent finer than and percent coarser than individual sieve sizes. A continuously sloping curve (curve A) represents a specimen with an even distribution of sizes. A vertical or horizontal drop in the curve (curves B and C) shows a sample with a heavy concentration of materials in limited sections of the total range.

Curve A in Fig. 8.5 is for a sample with good gradation. This type of soil is relatively stable, can be readily compacted, and is resistant to erosion. The bearing capacity and shear resistance of this soil are high. The sample of curve B depicts poor or uneven gradation. This sample is lacking particles between sieve sizes X_l and X_3. It is essentially made up of fines; coarser particles make up a very small fraction of the total sample. The sample of curve C is composed primarily of sieve size X_2. It contains very few fines and coarser particles. Compaction of soils, represented by curves B and C, is difficult.

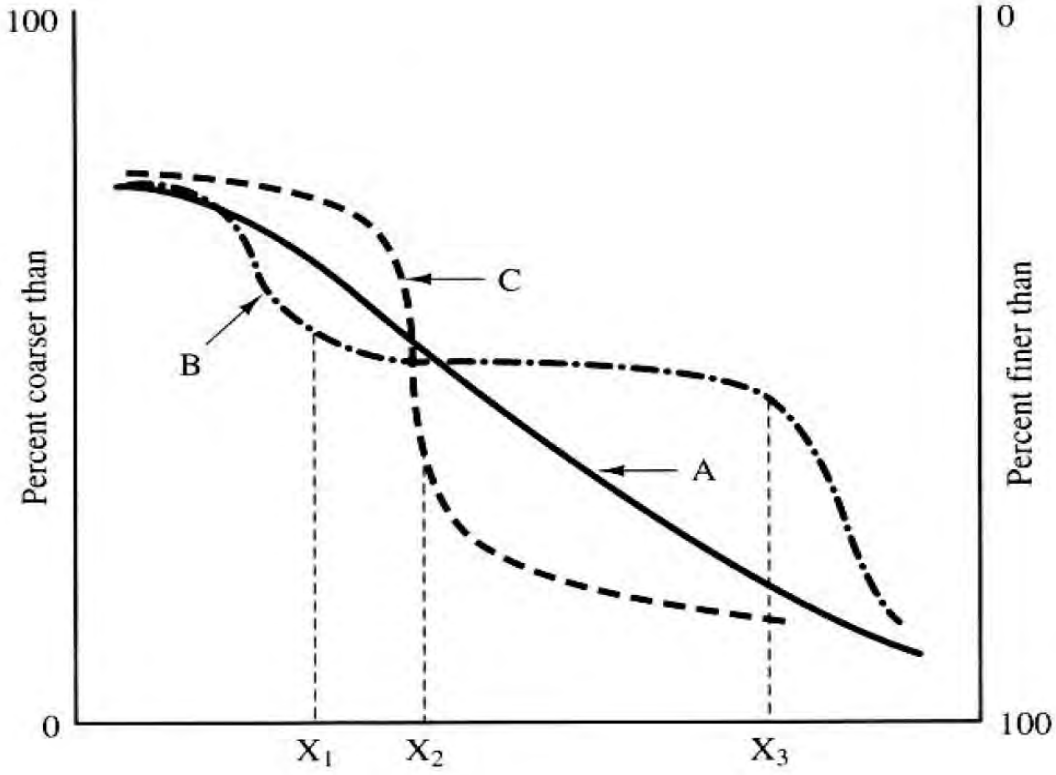


Figure 8.5 Particle-size distribution curves.

They are unstable. Gradation curves (grain-size curves) are also used in the identification and classification of soils.

Unit weight. If we take a sample of soil, it can be seen that it is made up of grains or particles, moisture and voids. The *voids* or pores are the open spaces between grains. Grains are particles of varying sizes, shapes, and mineral compositions. Moisture exists in the voids and makes the soil wet, damp, or dry. When the voids do not contain water, they are filled with air. When all the voids are filled with water, the soil is said to be saturated. If the soil is dried to constant weight in an oven (to drive off water from the voids), the weight is called *dry weight.*

The *unit weight* of soil is the weight of soil divided by the total soil volume, which is the solid volume plus the volume of voids. The weight of soil may be the weight of solids only, the weight of solids plus the weight of pore water, or the submerged weight of solids (Fig. 8.6).

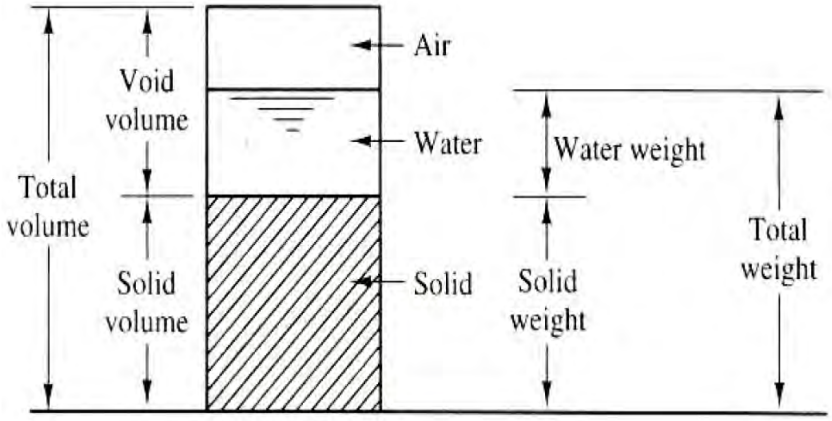


Figure 8.6 Weight-volume relationship of soil mass.

$$\text{unit weight of soil} = \frac{\text{soil weight}}{\text{total soil volume}}$$

When the soil weight includes the weight of solids only, the unit weight is called the *unit dry weight.* It is an index of the density of soil and depends on the concentration of solids in a given volume.

The dry unit weight of granular materials ranges between 80 and 130 pcf (1280 and 2080 kg/m^3). Clay soil has a dry unit weight between 50 and 105 pcf (800 and 1680 kg/m^3). The dry unit weight of mixed soils can be anywhere between 60 and 130 pcf (960 and 2080 kg/m^3). Organic matters decrease the unit dry weight. In organic silts and clays, the dry unit weight can be as low as 30 pcf (480 kg/m^3). When the soil is wet, the unit weight (wet unit weight) is higher. The submerged unit weight is the least of the three unit weights.

Moisture content. The moisture content or *water content* is the ratio of the weight of water to the weight of solids in the soil and is usually expressed as a percentage.

$$\text{Moisture content} = \frac{\text{weight of water}}{\text{weight of solids}} \times 100$$

The water content is determined by weighing the soil sample and then drying it in an oven at a temperature of about 230°F (110°C) (for a constant weight, normally 24 hours) and reweighing. Some marine and lake clays have a moisture content of 300 to 400%, and as high as 800%. Typically, fine-grained soils have a higher moisture content than that of coarse-grained soils. For moist sands the water content is less than 60%. The water content of the top layer of any soil deposits may not be the same as that of the bottom layer. Soils that appear dry may, in fact, contain water of 2 to 3%.

Water content is among the most frequently determined characteristics of soil. It is one of the more useful soil properties and is a good indicator of the shear strength of clays (saturated). When water is added to a dry soil, each particle is covered with a film of adsorbed water. Increasing the water will increase the thickness of this film of water. Increase in the thickness of the film allows the particles to slide easily past one another. Thus the behavior of a soil depends on the amount of water in the soil.

Water content plays an important role in the compaction of soils, especially of fine-grained soils. *Compaction* is a process of placing soil in a dense state. It is done to decrease settlement, increase shear strength, and decrease permeability. Earth dams, retaining walls, highways, airports, foundations, and embankments may require compacted soil.

Degree of saturation. The degree of saturation (S) is the ratio of the volume of water to the total volume of voidspace.

$$\text{Degree of saturation, } S = \frac{\text{volume of water}}{\text{volume of voids}} \times 100$$

or,

$$= \frac{\text{weight of water}}{w_w \times \text{volume of voids}} \times 100$$

where, w_w is the density of water. Volume of voids can be calculated as

$$\text{volume of voids} = \text{soil volume} = \frac{W_s}{SG \times w_w}$$

where, W_S· is the solid weight or dry weight of soil and SG is the specific gravity of soil.

Like moisture content, the degree of saturation is expressed as a percent. If the soil is dry, the degree of saturation is zero, and if the pores are full of water, the soil is saturated, and S= JOO%.

Natural deposits of soil below the water table have 100% degree of saturation. Due to capillary action, fine-grained soils above the water table may also be saturated. The *capillary action* refers to the rise of water in a capillary tube above the surrounding water level (Fig. 8.7). The height of rise depends on the diameter of the tube; the smaller the tube, the higher the rise inside it. In fine-grained soils, under certain conditions, water is retained through capillary action. Moisture on concrete floors of the basement or ground level may be through capillary action.

Degree of saturation affects the permeability of the soil. In addition, it has an effect on the shear strength and compressibility of the soil.

Void ratio. Void ratio (e) is the ratio of volume of voids to the volume of solids.

$$\text{Void ratio } e = \frac{\text{volume of voids}}{\text{volume of solids}}$$

or,

$$= \frac{SG(Ww)V - Ws}{WS}$$

where SG is the specific gravity of soil, *ww* the unit weight of water; Ws the solid weight or dry weight of soil, and *V* the total volume. Typical ranges of values of the void ratio for various type of soils are shown in Table 8.3. Generally, granular soils have a void ratio below 0.6 and cohesive soils have values greater than 0.7.

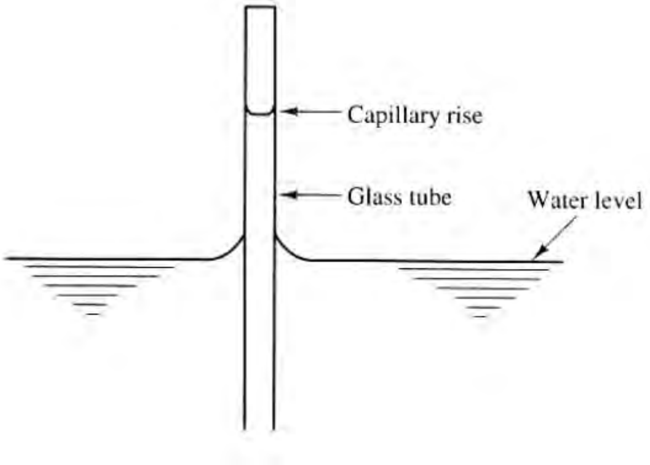


Figure 8.7 Capillary rise.

TABLE 8.3 AVERAGE PROPERTIES OF SOILS

Soil	Specific gravity	Void ratio
Gravel	2.5-2.8	0.25-0.33
Sand	2.6-2.7	0.30-0.54
Silt	2,64-2.66	0.35-0.85
Clay	2.55-2.75	0.42-0.96

Void ratio represents the denseness of a soil mass. Permeability, shear strength, and other properties are related to the void ratio. Compared to water content, the void ratio is a more important characteristic of the soil. In a given saturated soil, the void ratio is proportional to the water content.

Porosity. Porosity *(n)* is a property that also measures the void content in a soil sample, but is used more frequently by agricultural engineers. It is defined as the ratio between the volume of voids and the soil volume, expressed as a percentage.

$$\text{Porosity}, n = \frac{\text{volume of voids}}{\text{soil volume}} \times 100$$

or

$$= 1 - \frac{WS}{SG(w_w)V}$$

From comparing the definitions of porosity and void ratio, the following relationship can be derived:

$$e = \frac{n}{1-n}$$

And

$$n = \frac{e}{1+e}$$

Porosity, similar to void ratio, also measures the denseness of the soil. When a soil compresses or swells, the void volume changes, but the volume of solids remains the same. By comparing the equations for the void ratio and the porosity, it can be verified that the void ratio is a more convenient measure of volumetric changes in the soil than the porosity is. But when calculating the seepage through a soil, porosity is a more convenient measure.

Particle shape. In addition to the characteristics discussed above, the properties of coarse-grained soils depend on the shape of the particles. Depending on the length of transportation history, the particles can be angular, rounded, and well rounded (Fig. 8.8).

Angular particles allow more interlock between the grains than do rounded particles and thus offer greater frictional resistance. Particle shape also influences the density,

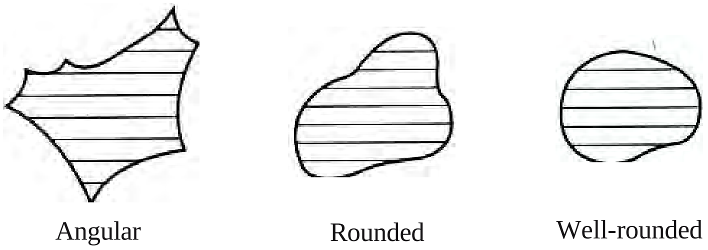


Figure 8.8 Shapes of particles.

compressibility, and shear strength of the soil. Typically, coarse-grained soils with angular particles have greater strength and bearing capacity than those of granular soils with rounded particles.

Specific gravity. Specific gravity (SG) is the ratio of the weight in air of a given volume of solid particles to the weight in air of an equal volume of distilled water. This property is used in relating the weight to the volume and in calculating the unit weight.

$$SG = \frac{\text{solid weight}}{(\text{volume of solids}) \times W_w}$$

The specific gravity of soils depends on the mineralogical composition. Some minerals, such as mica and dolomite, have high specific gravity (2.7 to 3.2); a few others, such as gypsum and bentonite, have low specific gravity (2.13 to 2.3). Ottawa sand has a specific gravity of 2.67. The specific gravity of clays may range between 2.2 and 2.75. Porous soils and soils with organic content may have a specific gravity less than 2.0. The specific gravity of most soils lies in the range 2.5 to 2.85.

Engineering properties of soil such as compressibility and shear strength depend on several factors and cannot be explained without a basic understanding of soil mechanics. These principles can be learned in a course on soil mechanics.

8.2.4 Uses of Soil

Well-graded sand, gravel, and sand-gravel mixtures are pervious when compacted. They possess excellent shear strength and negligible compressibility (following compaction). These types of soils constitute good construction material and can be used in foundations and roadways. Silty gravels and clayey gravels are excellent materials for rolled earth dams. They can also be used for road bases. Silts and clays with or without sands are impervious when compacted but possess poor shear strength. They have average compressibility characteristics and can be used for canal sections.

APPENDIX A

Illustrations

Figures A.1 Concrete is used in structures of various shapes and utilities such as a high-rise building (Fig. A.1). power plant chimneys (Fig. A-2). and domes (Fig. A-3).

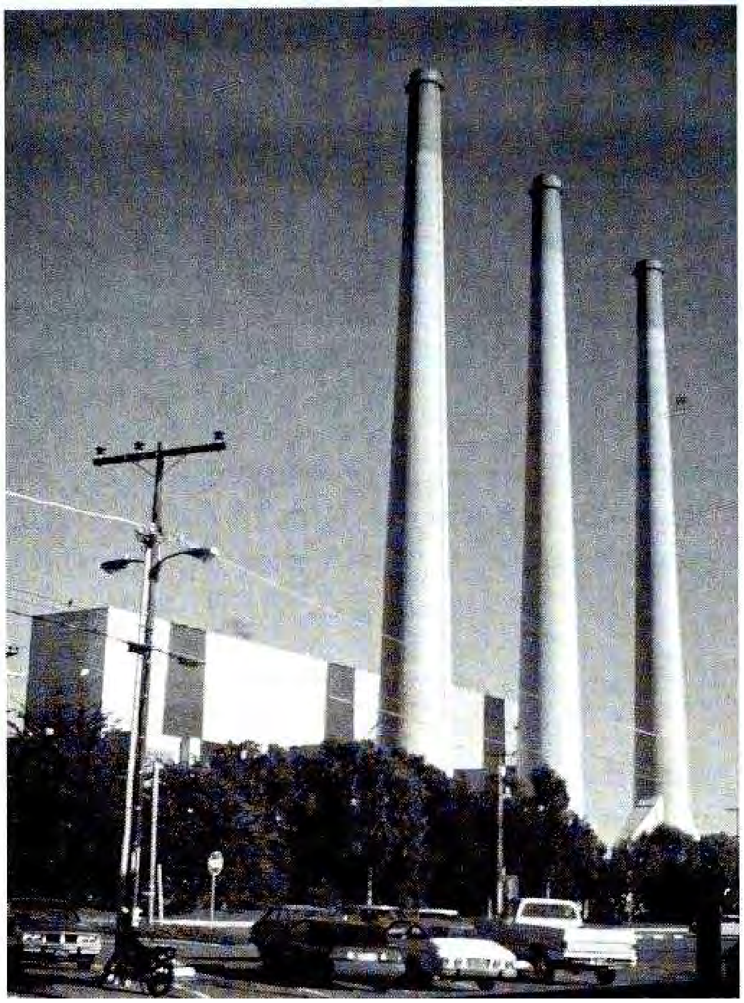


Figure A.2

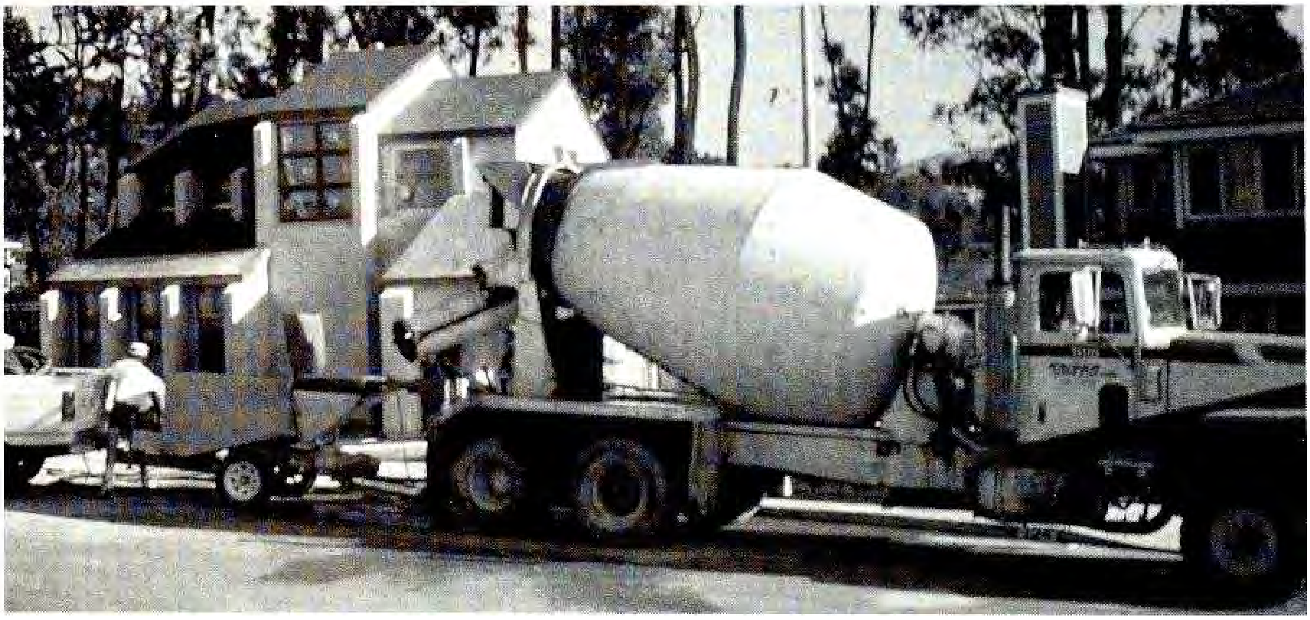


Figure A.4 Concrete is delivered to the job site in transmit mixes and using pumps.

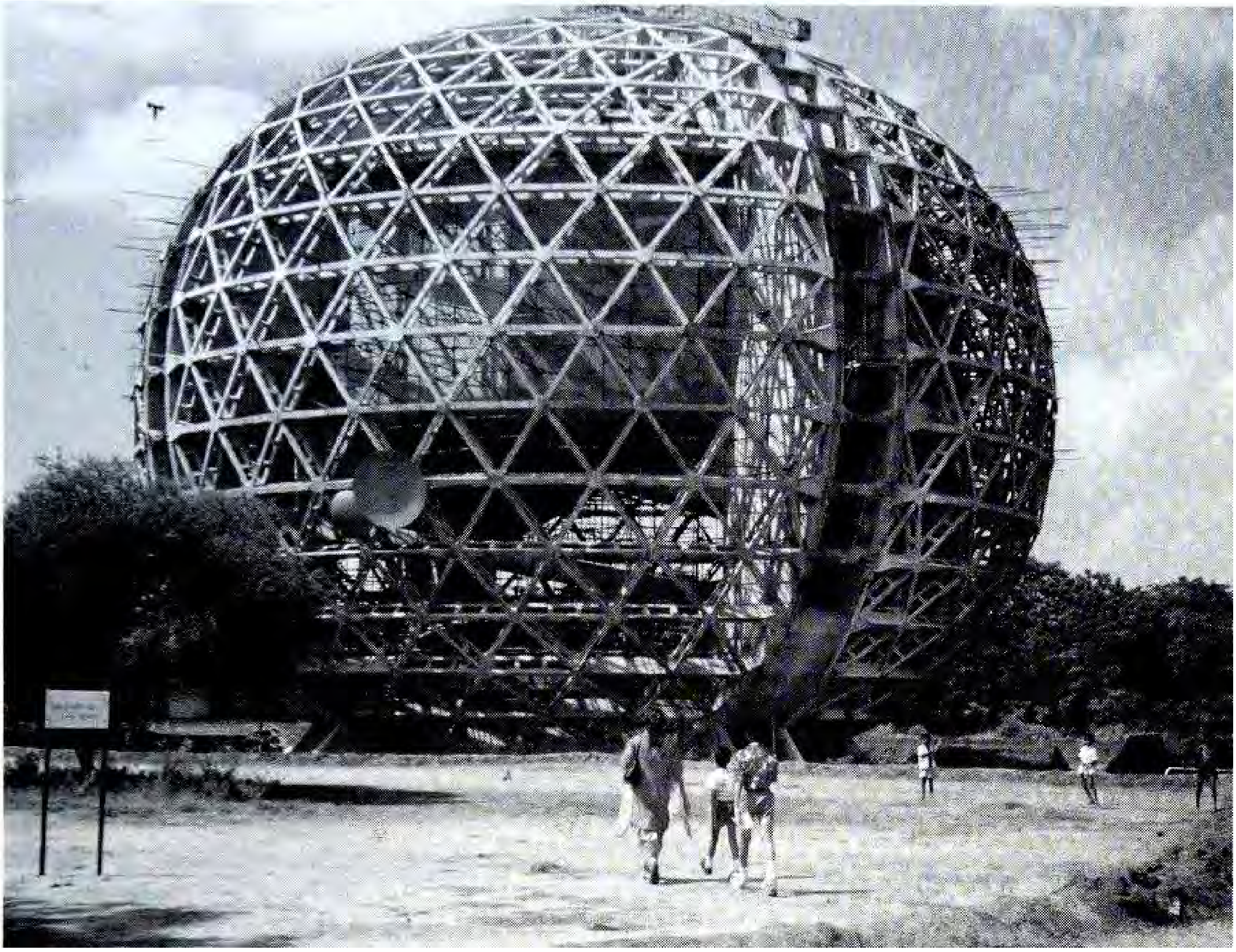


Figure A.3

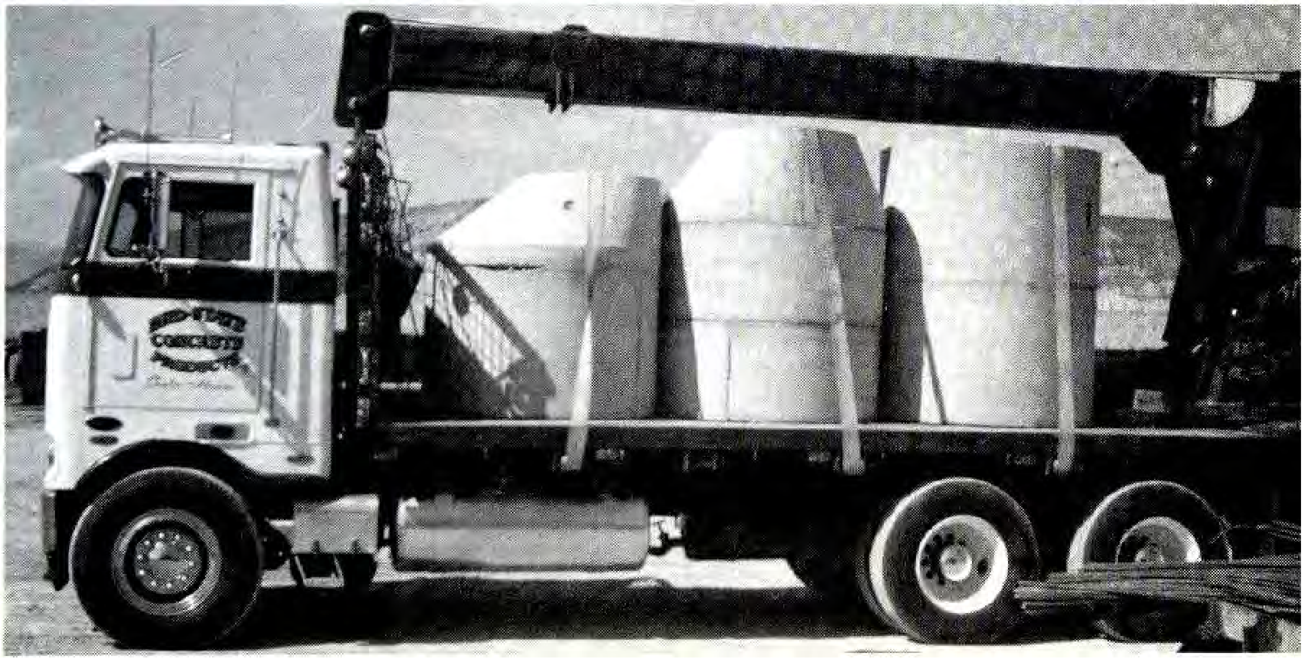


Figure A.5 Precast concrete element tire being hauled IO job site in truck

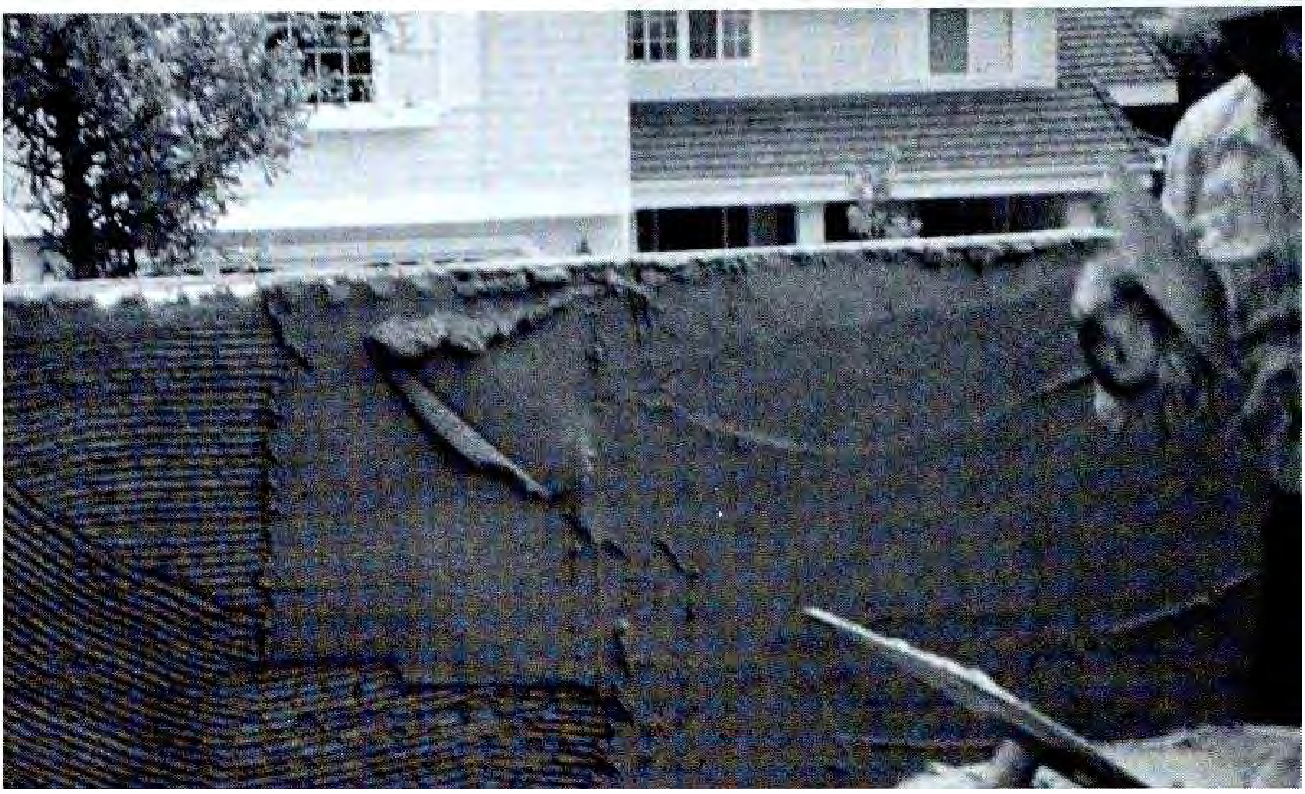


Figure A.6 Stucco is applied in three coats: Scratch coat, brown coat, and finish coat.

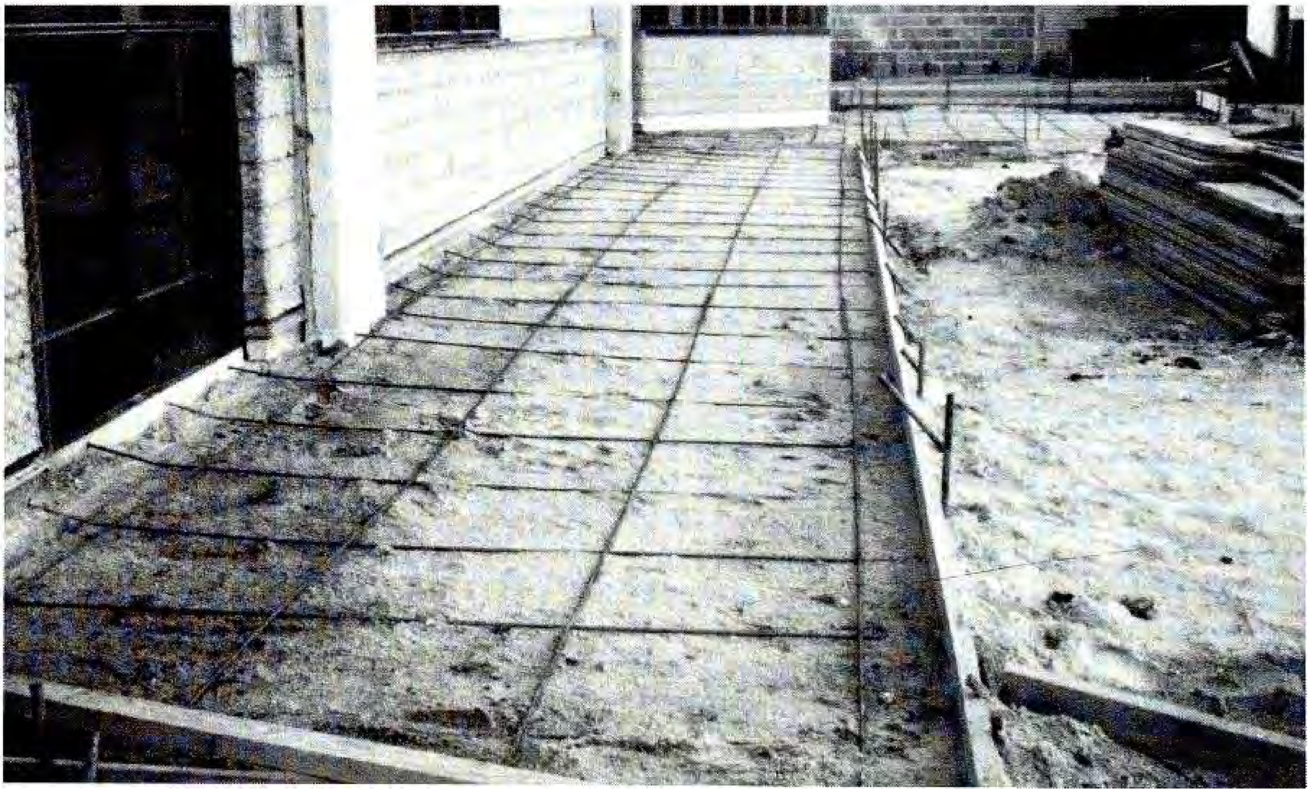


Figure A.7 Welded wire fabric is used for crack control in sidewalls and pavements.

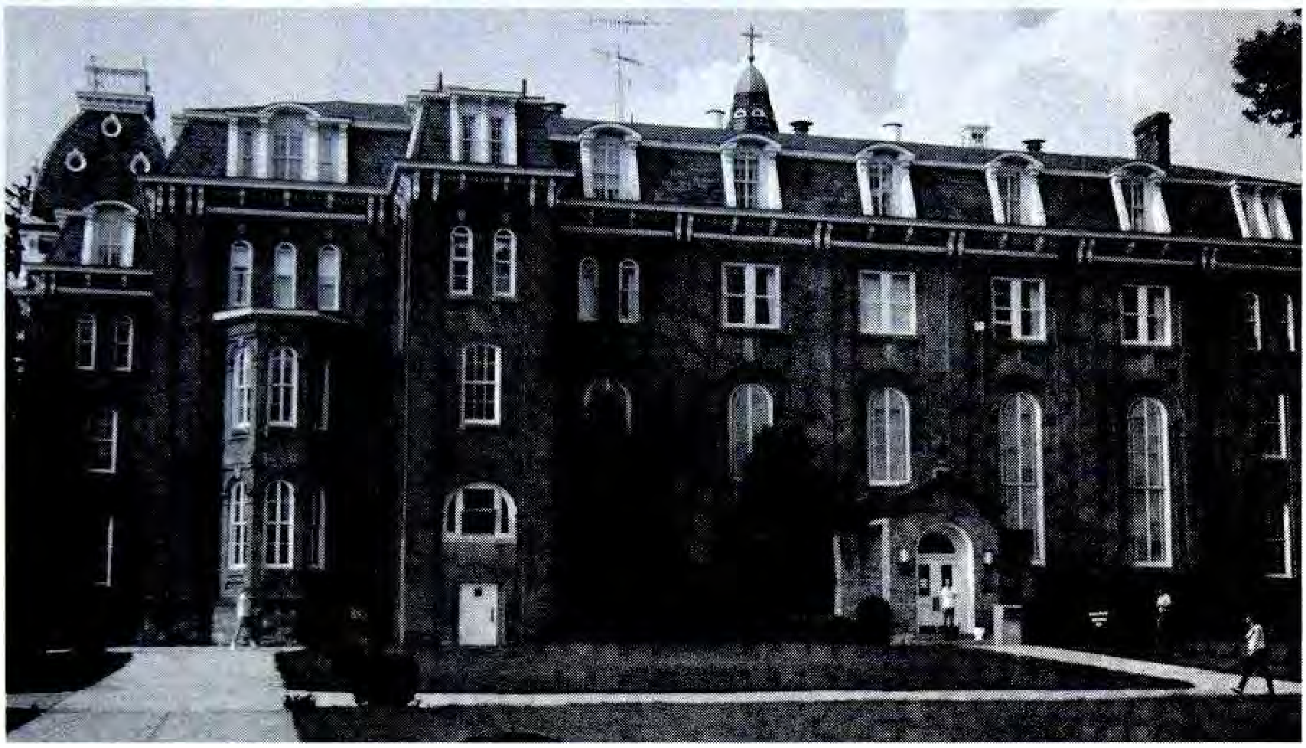


Figure A.8 Masonry is employed in the construction of tall buildings.

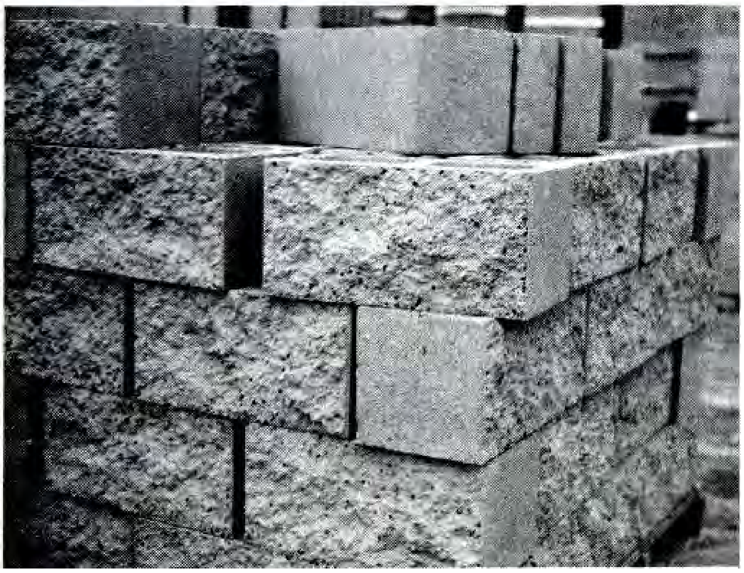


Figure A.9 Concrete masonry units come in varieties of shapes, colors and textures.

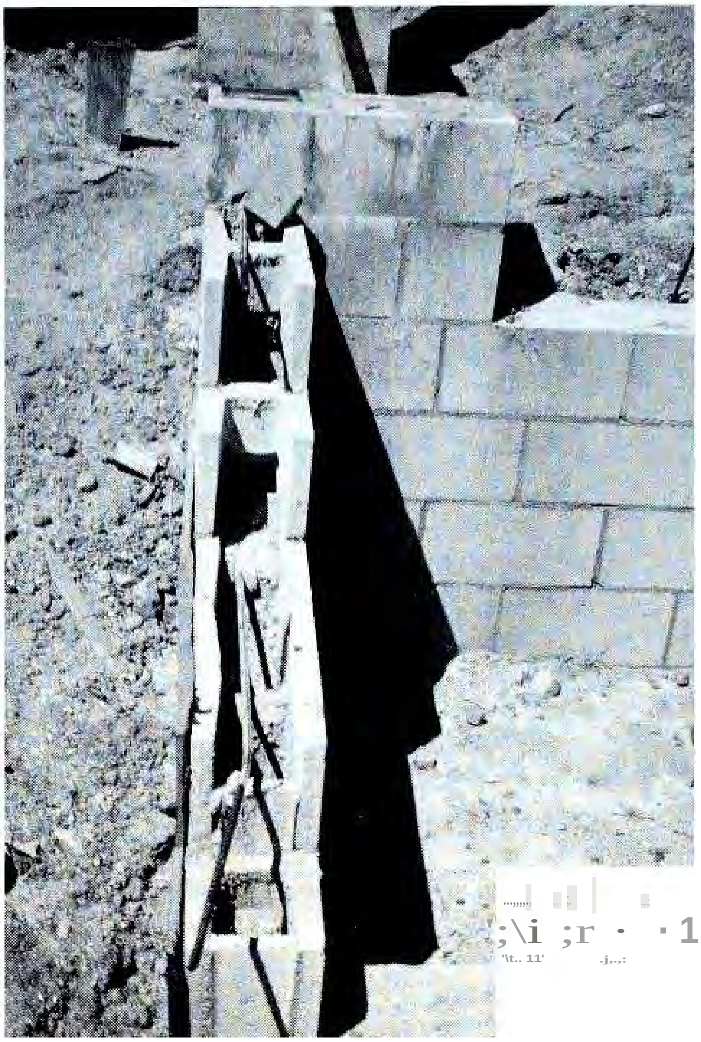


Figure A.IO Reinforced masonry materials and reinforcing steel.

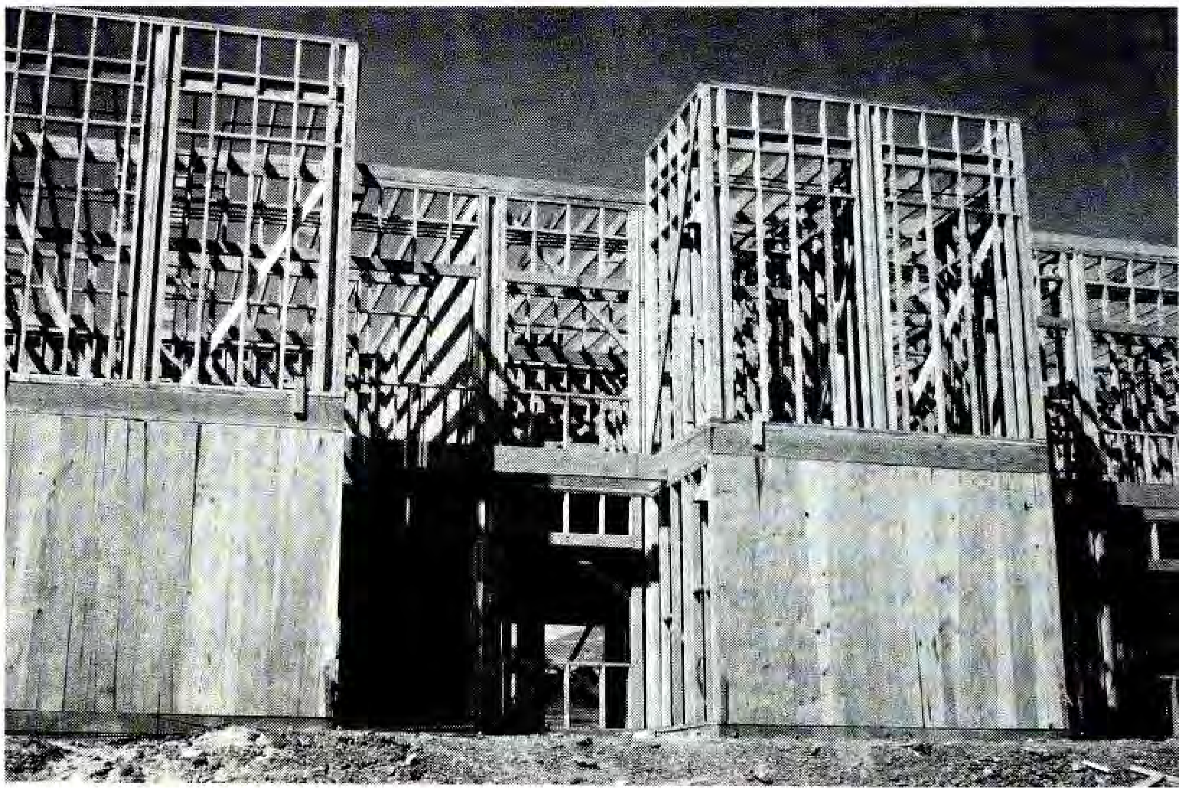


Figure A.11 Wood is the most common construction material for buildings of two to three stories.

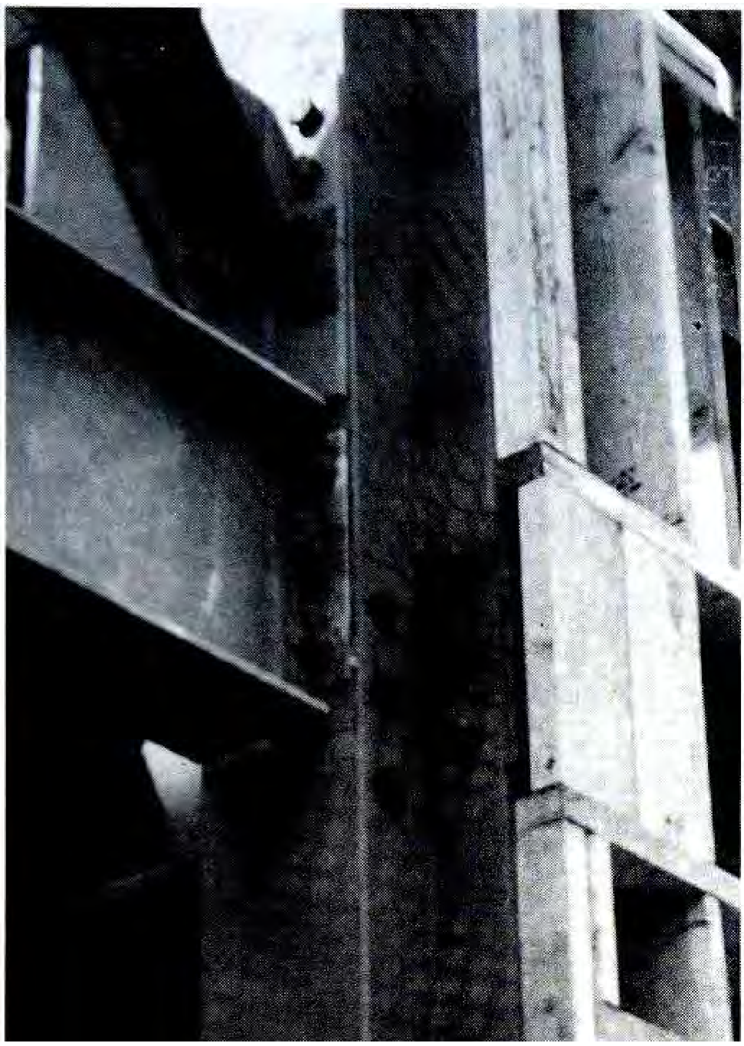


Figure A.12 Steel construction involves proper connections of structural steel

References and Further Reading

ABRAHAM, **H.** (1960-1962). *Asphalts and Allied Substances,* Vols.1-V. D. Van Nostrand, Princeton, N.J.

ACI COMMITTEE524 (1993). Guide to portland cement plastering. *AC/ Materials Journal,* 90(1), 69-93.

ADAMS, J. T. (1979). *The Complete Concrete, Masonry and Brick Handbook.* Arco Publishing, New York.

ADASKA, W. S. (1991). Soil-cement: a material with many applications. *Concrete International,* 13(1), 49-52.

AL-ADEEB, A. M., and AL-MUDHAF, H. A. (1992). Performance of masonry walls: case study in Kuwait. *Journal of Materials Engineering,* 4(1), 77-90.

AMERICANIRON ANDSTEEL INSTITUTE(1991). *The Pe,formance of Steel Buildings in Past Earthquakes.* **AJSI.** Washington, D.C.

AMERICAN IRON AND STEEL INSTITUTE(19??). *Steel Processing Flow Lines.* AISI, Washington, D.C.

AMERICANSOCIETY OF CIVIL ENGINEERS (1982). *Wood Structures: A Guide and Commentary.* ASCE, New York.

AMERICANSOCIETY FOR TESTING AND MATERIALS (1986). *Compilations of ASTM Standard Definitions.* ASTM, Philadelphia.

AMERICANSOCIETYFORTESTING AND MATERIALS (1991). *Annual Book of ASTM Standards,* Vol. 1.03 , *Steel: Plate, Sheet, Strip, Wire.* ASTM, Philadelphia.

AMERICAN SOOETY FOR TESTING AND MATERIALS (1991). *Annual Book of ASTM Standards,* Vol 1.04 , *Steel: Structural, Reinforcing, Pressure Vessel, Railway.* ASTM, Philadelphia.

AMERICAN SOCIETY FOR TESTING AND MATERIALS (I 99I). *Annual Book of ASTM Standards,* Vol. 4.01. *Cement; Lime_: Gypsum.* ASTM, Philadelphia.

AMERICAN SOCIETY FOR TESTING AND MATERIALS (1991). *Annual Book of ASTM Standards,* Vol. 4.02. *Concrete and Aggregates.* **ASTM,** Philadelphia.

AMERICAN SOCIETY FOR TESTING AND MATERIALS (1991). *Annual Book of ASTM Standards,* Vol. 4.03. *Road and Paving Materials; Pavement Management Technologies.* **ASTM,** Philadelphia.

AMERICAN SocU::.,Y FOR TESTING AND MATERIALS (1991). *Annual Book of ASTM Standards,* Vol. 4.04, *Roofing, Waterproofing and Bituminous Materials.* **ASTM,** Philadelphia.

AMERICAN SOCIETY FOR TESTING AND MATERJALS (199J). *Annual Book of ASTM Standards,* Vol. 4.05, *Chemical Resistant Materials; Vitrified Clay, Concrete, Fiber-Cement Products; Mortars; Masonry.* **ASTM,** Philadelphia.

AMERICAN SOCIETY FOR TESTING AND MATERIALS (1991). *Annual Book of ASTM Standards,* Vol. 4.08, *Soil and Rock; Dimension Stone; Geosynthetics.* **ASTM,** Philadelphia.

AMERICAN SOCIETY FOR TESTING AND MATERIALS (1991). *Annual Book of ASTM Standards,* Vol. 4.09, *Wood.* ASTM, Philadelphia.

ANON. (1980). Control of cracking in concrete structures. *Concrete International,* Oct., 80, 35-76.

ANON. (1991). Proposed revisions of guide to durable concrete. *AC/ Materials Journal,* Sept-Oct. 544-574.

ANON. (1993). *Fiber-Reinforced Plastics International,* 1(1).

ARNTSON, **J.** H. (1967). *Roadwork Technology,* Vol. 2. Iliffe Books, London.

ATKINS, H. N. (1983). *Highway Materials: Soils and Concretes,* 2nd ed. Reston, Reston, Ya.

BAALBAKI, W., BENMOKRANE, B., CHAALLAL, 0., AND AITCIN, **P.** C. (1991). *AC/ Materials Journal,* 88(5), 499-510.

BAKER, I. 0. (1899). *A Treatise on Masomy Construction,* 9th ed. Wiley, New York.

BAUER, E. E. (I 949). *Plain Concrete,* 3rd ed. McGraw-Hill, New York.

BENJAMIN, B. S. (1982). *Structural Design with Plastics.* Yan Nostrand Reinhold, New York.

BERGER, B. 0., AND ANDERSON, K. E.(1978). *Modern Petroleum.* Petroleum Publishing, Tulsa Okla.

BERRY, E. E., AND MALHOTRA, V. M. (1980). Fly ash for use in concrete: a critical review. *AC! Journal,* 77(2), 59-73.

BETHLEHEM STEEL (19??). *Sparrows Point Plant.* Bethlehem Steel Corporation, Bethlehem, Pa.

BETHLEHEM STEEL (19??) *The Steel Making Process.* Bethlehem Steel Corporation, Bethlehem, Pa.

BISWAS, A. **K.** *(* 1981). *Principles of Blast Furnace Ironmaking.* Cootha Publishing House, Brisbane. Australia.

BOWLES, .I.E. (1984). *Physical and Geotechnica/ Properties of Soils* 2nd ed. McGraw-Hill, New York.

BOWMAN, M. D., AND BETANCOURT, **M.** (1991). Reuse of A325 and A490 high strength bolts., *Engineering Joumal,* 28(3), 1 I 0-118.

BRABSTON, W. N., AND ROLLINGS, R. S. (1991). Design of cement stabilized base course for airfield pavements. *Concrete lnterrw1ional.* 13(12), 19-23.

BRUNSKILL, R., AND CLIFTON-TAYLOR. A. (1977). *English Brickwork.* A Hyperion Book. Ward Lock, London.

CAPPER, P. L., AND CASSLE, **W. F.** (1969). *The Mechanics of Engineering Soils.* E. and **F. N.** Spon, London.

CHAALLAL, 0., BENMOKRANE, B., AND BALLJVY, G. (1992). Drying shrinkage strains: experimental versus codes. *AC/ Materials Journal,* 89(3), 263-266.

CHIUNGARIAN, G. V., AND YEN, T. F. (Eds.) (1978). *Bitumens, Asphalts and Tar Sands.* Elsevier, New York.

COHEN, M. D., OLEK, J., AND MATHEW, B. (1991). Silica fume improves expansive-cement concrete. *Concrete International,* 13(3), 31-37.

COMMITTEEON ENGINEERING MATERIALS, **ASTM.** (l958) *Engineering Materials.* ***ASTM*** **Pitman,** New York.

CONCRETE REINFORCINGSTEEL INSTITUTE (1986). *Manual of Standard Practice.* CRSI, Schaumburg, lll.

CONCRETE REINFORCINGSTEEL INSTITUTE (1986) *Placing Reinforcing Bars.* **CRSJ,** Schaumburg, Ill.

CONCRETE REINFORCING STEEL INSTITUTE(1992). *The Tallest Reinforced Concrete Building in Seismic Zone IV.* CRSI, Schaumburg, JJl.

CORDON, W. A. (1979). *Properties, Evaluation and Control of Engineering Materials.* McGraw-Hill, New York.

CRAI.G, R. F. (1983). *Soil Mechanics.* Van Nostrand Reinhold, Wokingham, Berkshire, England.

DALLAIRE, G. (1983). Superplasticizer concrete takes off in Dallas. *Civil Engineering,* Mar., 39-41.

DAVEY, N. (1961). *A History of Building Materials.* Phoenix House, London.

DAVIS, H. E., TROXELL, G. E., AND HAUCK, G. F. W. (1982). *The Testing of Engineering Materials,* 4th ed. McGraw-Hill, New York.

DAVIS, H. E., TROXELL, G. E., AND WISKOCIL, C. T. (1964). *The Testing and Inspection of Engineering Materials.* McGraw-Hill, New York.

DAY, R. (1979). *The Practical Handbook of Concrete and Masonry.* Arco Publishing, New York.

DECAMP, L. S. (1972). *Great Cities of the Ancient World.* Doubleday, New York.

DENNIS, W. H. (1967). *Foundations of Iron and Steel Metallurgy.* Elsevier, Barking, Essex, England.

DERUCHER, K. N. AND KORFIATIS, G. P. (1988). *Materials/or Civil and Highway Engineers.* Prentice Hall, Englewood Cliffs, N.J.

DOLAR-MANTAUANI, L. (1983). *Handbook of Concrete Aggregates.* Noyes Publications, Park Ridge, N.J.

DUB0VOY, V. S., ANDRI.BAR, J. W.(1990). *MaSOnl)' Cement Mortar: A Laboratory Investigation.* Research and Development Bulletin RD0095 Portland Cement Association, Skokie, Ill.

DUNCAN, C. I. (1992). *Soils and Foundations/or Architects and Engineers.* Van Nostrand Reinhold, New York.

ENGLNEERING EQUIPMENT USERS ASSOCIATION, (1973). *The Uses of Plastic Materials in Buildings.* Handbook, E E U A, London.

FLETCHER, B. (1954). *A History of Architecture on the Comparative Method,* 16th ed. Raphael Tuck, England.

FLINN, **R.** A., AND TROJAN, **P. K.** (1975). *Engineering Materials and Their Applications.* Houghton Mifflin, Boston.

GARBER, N. J., AND HOEL, L.A. (1988). *Traffic and Highway Engineering.* West Publishing, St. Paul, Minn.

GARRATY, J. A., AND GAY, P. (Eds.) (1981). *The Columbia History of the World.* Harper & Row, New York.

GEBLER, S. H., AND KLIEGER, P. (1986). *Effect of Fly Ash on Some of the Physical Properties of Concrete.* Portland Cement Association, Skokie, Ill.

GrACCI0, G., Rocco, C., VIOLIN(, D.. ZAPPITELLI, J., AND ZERBIN0, R. (1992). High-strength concretes incorporating different coarse aggregates. *AC/ Materials Journal,* 89(3), 242-246.

GUSTAFSON, D. P.. AND FELDER, A. L. (1991). Questions and answers on ASTM A706 reinforcing bars. *Concrete International,* 13(7), 54-57.

HALL, C. (1989). *Polymer Materials,* 2nd ed. Wiley, New York.

HAQUE, M. N., AND KAWAMURA, M. (1992). Carbonation and chloride-induced corrosion of reinforcement in fly ash concretes. *AC/ Materials Journal,* 89(1), 41-48.

HEINZ, R. (1993). Plastic piling. *Civil Engineering,* 63(4), 63-65.

HODSON, R., AND KUSHNER, D. D. (1992). Ingredients, texture, and integrally colored concrete. *Concrete International,* Sept., 21-25.

HOUGH, B. K. (1957). *Basic Soils Engineering.* Ronald Press New York.

HOYLE, R. J., ANDWOESTE, F. E. (1989). *Wood Technology in the Design of Structures,* 5th ed. Iowa University Press, Ames, Iowa.

JACKSON, N:, AND DHIR, R. K. (1988). *Structural Engineering Materials.* Hemisphere, New York.

JOHNSON, A. (1992). Steel weighs in. Civil Engineering, July, 69-7l.

K.Al'ffRO, D. L. (1981). *Influence of Water Reducing Admixtures on Properties of Cement Paste: A Miniature Slump Test.* Research and Development Bulletin RD079.0IT. Portland Cement Association, Skokie, Ill.

KECK, R. (1991). A tower of strength. *Concrete International,* I3(3), 23-25.

KINNEY, G. F. (1957). *Engineering Properties of Plastics and Applications.* Wiley, New York.

KNOWLES, P. (1977). *Design of Structural Steelwork.* Surrey University Press, London.

KORHONEA, C. J., AND CORTEZ, E. R. (1991). Antifreeze admixtures for cold weather concreting. *Concrete International,* 13(3), 38-41.

KREBS, R. D., AND WALKER, R. D. (1971). *Highway Materials.* McGraw-Hill. New York.

LARSON, T. D. (I 963). *Portland Cement and Asphalt Concretes.* McGraw-Hill, New York.

LAY, M. G. (1986). *Handbook of Road Technology,* Vol. I. Gordon and Breach, New York.

LEA, F. M. (1970). *The Chemistry of Cement and Concrete,* 3rd ed. Edward Arnold, London.

LEVER, A. E. (1968). *The Properties and Testing of Plastics Materials.* 3rd ed. Temple Press Books. Feltham, Middlesex, England.

Loov, R. E. (1991). Reinforced concrete at the turn of the century. *Concrete International,* Dec., 67-73.

MAJKO, R. M., AND PISTILLI, M. F. (1984). Optimizing the amount of Class C fly ash in concrete mixtures. *Cement, Concrete and Aggregates,* 6(2). 105-119.

MCCRUM, N. G., BUCKLEY, C. P., AND BUCKNALL, C. B. (1989). *Principles of Polymer Engineering.* Oxford University Press, Oxford.

MEININGER, R. C. (1988). No-fines pervious concrete for paving. *Concrete International,* 10(8), 20-29.

MILLS, A. P., HAYWARD, H. W., AND RADER, L. F. (1965). *Materials <Jconstruction,* 6th ed. Wiley, New York.

MURDOCK, L. J., AND BROOK, K. M. (1978). *Concrete Materials and Practice.* Wiley, New York.

NEVILLE, A. M. (1971). *Hardened Concrete: Physical and Mechanical Aspects.* ACI Monograph Series. American Concrete Institute, Detroit, Mich.

NEVILLE, A. **M.,** AND BROOKS, **J. J.** (1987). *Concrete Technology.* Longman, Harlow, Essex, England.

NUCOR (19??) *The Nucor Story.* Nucor Corporation, Charlotte, N.C.

O'FLAHERTY, C. A. (1988). *Highways,* Vol. 2, 3rd ed. Edward Arnold, London.

PARE, T. P. (1991). The big threat to big steel's future. *Fortune.*

PEACEY, **J.** G., AND DAVENPORT, W. G. (1979). *The Iron Blast Furnace.* Pergamon Press, Oxford.

PISTILLI, M. F., WJNTERSTEEN, R., AND CECHNER, R. (1984). The uniformity and influence of silica fume from a U.S. source on the properties of portland cement concrete. *Cement, Concrete, and Aggregates,* 6(2), 114-120.

P1rrs, J. (1984). *A Manual of Geology for Civil Engineers.* Wiley New York.

PLUMMER, H. C. (1962). *Bricks and Tile Engineering.* Brick Institute of America, McLean, Va.

POLLACK, H. W. (1977). *Material Science and Metallurgy,* 2nd ed. Reston, Reston, Va.

PORTLANDCEMENT ASSOCIATION PCA, (197 l). *High Strength Concrete.* Skokie, Ill.

PORTLANDCEMENT ASSOCIATION(1976) *Concrete Masonry Handbook for Architects, Engineers and Builders.* PCA, Skokie, Ill.

PORTLANDCEMENT ASSOCIATION (1980). *Portland Cement Plaster (Stucco) Manual.* PCA, Skokie, Ill.

PORTLAND CEMENT ASSOCIATION (1987). *Mortars for Masonry Walls.* (1987). PCA, Skokie, Ill.

PORTLANDCEMENT ASSOCIATION (1983) *Concrete Floors on Ground,* 2nd ed. PCA, Skokie, m.

PORTLANDCEMENT ASSOCIATION (1987) *Recommended Practices for Laying Concrete Block.* PCA, Skokie, IL.

PORTLANDCEMENT ASSOCIATION (J 991). *Masonry Information.* PCA, Skokie, Ill.

PRICE, **W. H.** (1982). Control of cracking of concrete during construction. *Concrete International,* 4(1), 40-43.

QUARMBY, A. (1974). *The Plastics Architect.* Pall Mall Press, London.

RAGSDALE, **L.** A., AND RAYNHAM, E. A. (1972). *Building Materials Technology.* Edward Arnold, London.

RASHEEDUZZAFAR(1992). Influence of Cement Composition on Concrete Durability. *AC/ Materials Journal,* 89(6), 574-586.

REBOUL, P., AND MITCHELL, R. G. 8. (1968). *Plastics in the Building Industry.* George Newnes, London.

RIBAR, J. W. (1990). *Water Permeance of Masonry: A Laboratory Study.* **ASTM STP** 778. American Society for Testing and Materials, Philadelphia, pp. 200-220.

RICE, W. H. (1982). Control of cracking in concrete during construction. *Concrete International,* Jan., 40-43.

ROBERTS, W. L. (1983). *Hot Rolling of Steel.* Marcel Dekker, New York.

ROPKE. J.C. (1982). *Concrete Problems: Causes and Cures.* McGraw-Hill, New York.

SCHRADER, E. (1992). Mistakes, misconceptions, and controversial issues concerning concrete and concrete repairs. *Concrete International,*Sept., 52-56.

SENBETTA, E. (1989). Curing compound selection. *Concrete International,* Feb., 65-67.

SHAH, S. P. (Ed.) (1979). *Proc. Workshop on High-Strength Concrete,* Dec. 2-4, 1979, University of Illinois at Chicago.

SHARP, J. D. (1966). *Electric Steelmaking.* lliffe Books. London.

SmLSTONE, J. M. (l 99l). Performance specifications for concrete pavement. *Concrete International,* 13(12), 28-34.

SMITH, R. C. (1979). *Materials of Construction.* 3rd ed. McGraw-Hill, New York.

SOMAYAJI, S. (1990). *Structural Wood Design.* West Publishing, Minneapolis, Minn.

SOROKA, I. (L979). *Portland Cement Paste and Concrete.* Chemical Publishing, New York.

SPEARS, R. E. (1983). The 80 percent solution to inadequate curing problems. *Concrete International,* 5(4), 15-22.

SPENCE, R. J. S., AND COOK, 0. J. (1983). *Building Materials in Developing Countries.* Wiley, New York.

STODOLA, P. R. (1983). Performance of fly ash in hardened concrete. *Concrete International,* 5(12), 64-68.

STOLL, T. M., AND EVSTRATOV, G. I. (1987). *Building in Hot Climate.* MIR Publishers, Moscow.

TAYLOR, W. H. (1967). *Concrete Technology and Practice.* Angus and Robertson, Sydney, Australia.

TRANSPORTATION RESEARCHBOARD TRB, (1975). *Bituminous Emulsions for Highway Pavements.* National Research Council, Washington. D.C.

TRANSPORTATIONRESEARCHBOARD (1984). *Asphalt Overlay Design Procedure* TRB, National Research Council, Washington, D.C.

TRANSPORTATION RESEARCHBOARD (1988). *Low Temperature Properties of Paving Asphalts Cements.* TRF National Research Council, Washington, D.C.

TUTHILL, L. H. (l 982). Alkali-silica reaction: 40 years later. *Concrete International,* 4(4), 32-36.

TUTHILL, L. H. (1991). Long service life of concrete. *Concrete International,* 13(7). 15-17.

VONDRON, G. L. (1991). Applications of steel fiber reinforced concrete. *Concrete International,* 13(1I), 44-49.

WALLACE, H. A. AND MARTIN, J. R. (1967). *Asphalt and Pavement Engineering.* McGraw-Hill, New York.

WATSON, D. A. (1978). *Construction Materials and Processes,* 2nd ed. McGraw-Hill, New York.

WJLUN, Z., AND STARZEWSKI, K. (1972). *Soil Mechanics in Foundation Engineering.* Wiley, New York.

WIRE REINFORCEMENT INSTITUTE(1991). *Reinforcing Steel in Slabs-on-Grade.* Tech Facts TF 70I. WRI, Washington, D.C.

WIRE REINFORCEMENT INSTITUTE(1992). *How to Specify, Order and Use Welded Wire Fabric in Light Construction.* Tech Facts TF 202. WRI, Washington, D.C.

(1973). *The World of Plastics.* Young Readers Press, New York.

WRIGHT, P.H., AND PAQUETrE, R. J. (1987). *Highway Engineering,* 5th ed. Wiley, New York.

ZOLLO, R. F., ANDHAvs, C. D. *(* I991). Fiber vs. WWF as nonstructural slab reinforcement. *Concrete International,* 13(11), 50-55.

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Civil Engineering Materials

Shan Somayaji

Whether above ground, underground, offshore, or inland, civil engineers are designing, constructing, maintaining, inspecting, and managing a diversity of public works projects. Comprehensive in scope, this book was designed to help readers fully understand the engineering principles underlying the selection of basic materials used in most types of construction projects. Author **Shan Somayaji** offers a comprehensive overview of civil engineering materials, complete with a wealth of learning aids that provide strong reinforcement. End-of-chapter material includes step-by-step testing procedures to determine the properties of materials.

Topics include:

- Aggregates
- Concrete and Other Cementitious Materials
- Masonry
- Wood and Wood Products
- Bituminous Materials
- Iron and Steel
- Plastics, Rocks, and Soils

ISBN 0-13-177b FE,

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